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REVIEW OF RTG UTILIZATION IN SPACE MISSIONS

ORIGINAL

COMPLETED

HEARING

BEFORE THE

SUBCOMMITTEE ON
ENERGY RESEARCH AND PRODUCTION

AND THE

SUBCOMMITTEE ON
SPACE SCIENCE AND APPLICATIONS

OF THE

COMMITTEE ON SCIENCE AND TECHNOLOGY HOUSE OF REPRESENTATIVES

NINETY-NINTH CONGRESS

SECOND SESSION

MARCH 4, 1986

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**Serving on Committee on the Budget for 99th Congress.

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REVIEW OF RTG UTILIZATION IN SPACE MISSIONS

TUESDAY, MARCH 4, 1986

HOUSE OF REPRESENTATIVES, COMMITTEE ON SCIENCE AND TECHNOLOGY, SUBCOMMITTEE ON ENERGY RESEARCH AND PRODUCTION, AND THE SUBCOMMITTEE ON SPACE, SCIENCE AND APPLICATIONS,

Washington, DC.

The subcommittees met, pursuant to notice, at 2:02 p.m., in room 2318, Rayburn House Office Building, Hon. Marilyn Lloyd (chairman of the Subcommittee on Energy Research and Production) presiding.

Mrs. LLOYD. The subcommittees will come to order. Good afternoon, ladies and gentlemen. I'm very happy to see you today. I believe it is very important to understand what we are about in this hearing on RTG's for space missions today. This is not an investigative hearing. Rather, it is a legislative and oversight hearing aimed at defining budget requirements and capturing lessons learned for space nuclear power.

The two subcommittees are strongly supportive of the manner in which the committee is approaching the *Challenger* accident investigation. The committee's special steering group is monitoring the Presidential Commission's progress and the committee will review the Commission's findings and then report to the whole House. Until the investigation is complete, as Chairman Fuqua has noted, we can only do a disservice by seizing on fragmentary information and deriving prematurely reckless conclusions in the absence of a comprehensive picture.

As most of you know, radioisotope thermoelectric generators, or RTG's, utilize a nuclear emitter to provide heat which is converted to electricity for onboard power. This is properly a joint hearing since the Energy Research and Production Subcommittee authorizes DOE's RTG development and fabrication activities, while Space Science and Applications authorizes NASA's funding for missions such as Ulysses and Galileo. It appears that these missions will now be delayed by at least 15 months, and thus DOE and NASA have time to perform further analyses and even RTG-related safety testing if that is required.

I am most interested in determining what level of DOE funding will be required in fiscal year 1987 to provide for this contingency. This is the fifth ERP oversight hearing, and our second joint hearing on space nuclear in the past 3 years.

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The United States has a successful history of 25 years experience with RTG's in space. There have been 22 missions with 38 RTG's flown and the 3 mission failures that carried RTG's on the spacecrafts have caused no harm to health, safety, or threat to environment. Nevertheless, DOE and NASA have continued to perform safety analyses and tests to provide improved confidence that RTG's can be flown on future missions. As previous missions have demonstrated, neither our civilian nor our national security programs can go forward without these atomic batteries, so we must assess how we can best proceed while mitigating any potential impacts.

Today we shall hear about accident probabilities about radiation source terms, and ultimately risk assessments. I do hope that our witnesses today will help clarify this terminology and outline clearly the relationship between potential RTG accidents and the risks which they pose to people. As we who are familiar with nuclear power well know, extremely improbable events do not pose significant risks. Yet improbable consequences have been misleadingly used to suggest great danger. So as we proceed, I hope that we can keep these different aspects of the risk-assessment approach in context.

The Congress has a special responsibility to demonstrate, and as Chairman Fuqua noted, measured restraint. In that way, we can set a tone for careful, reasoned deliberation on the Commission's report when it is submitted, and we most certainly shall approach today's hearing in that spirit.

We shall also discuss the executive branch process for assuring the safety of RTG space flights which involves NASA, DOD, and the Department of Energy. The Interagency Nuclear Safety Review Panel is a truly independent panel as is evidenced by the studies which they have conducted to obtain separate assessments of critical safety issues. We shall, of course, hear from the DOE on the RTG Program so we can better understand these activities and identify additional tasks which might be required in fiscal year 1987.

We shall also take testimony from the national laboratories who are the field centers for analysis and testing and Teledyne Corp. who contracted for a report which has become somewhat controversial. I believe we can place that issue of engineering estimates versus probabilistic risk assessments in context in today's hearing. I also believe that we can fulfill our legislative and oversight responsibilities today in the fine tradition of the Science Committee.

As regards time, we must ask DOE, NASA, and our INSRP witnesses to summarize for 10 minutes or less and our panelists to try for 5 minutes. Mr. Nelson and I are prepared to go late, and I am sure that Mr. Morrison will agree with us on this. We may be forced to abandon the 5-minute rule at some point and limit our questions to our members. In any event, I would encourage the members to submit written questions for the record.

Now, I would like to call on my good friend and cochairman, Mr. Bill Nelson, from the Space Science and Application Subcommittee for his opening remarks. Congressman Nelson.

Mr. NELSON. Thank you, Madam Chairman. I appreciate, Madam Chairman, this opportunity under your leadership to have this

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joint hearing. And the question is: Is it safe or not? That is what we want to learn. The flying of radioactive payloads aboard the space shuttle—we certainly know we have to have these radioactive payloads if we are going to explore the outer reaches of the solar system.

For example, extraordinary photos and information that we have had come back from Viking, Voyager, and Pioneer has had as an energy source a nuclear source of energy. The Sun just doesn't shine brightly enough in the far reaches of the universe in order to generate through photovoltaic cells, the energy needs that are required. So the question is now, since we have had this tragic, tragic accident with *Challenger*, whether or not, since the questions have been raised, whether or not it is safe to fly. So I am looking forward, under your leadership for our two committees to pursue this. Thank you, Madam Chairman.

[The prepared opening statement of Mr. Nelson follows:]

OPENING STATEMENT OF HON. BILL NELSON

I am pleased to have the Space Science and Applications Subcommittee participating with the Energy Research and Production Subcommittee on this important matter. By combining the energy and space jurisdictions and expertise of our two Subcommittees, these hearings will clearly be more effective and complete than if we were to conduct our oversight activities separately.

The recent Challenger accident has raised questions in many people's minds—both in Congress and in the general public—regarding the safety of flying radioactive payloads onboard the Space Shuttle. Such payloads need to be flown if the United States is to pursue an active program to explore the outer planets.

On the other hand, it would clearly not be prudent to fly these payloads on the Space Shuttle before the safety concerns that have been raised as a result of the Challenger accident have been fully scrutinized.

I look forward to this opportunity that our two Subcommittees have to jointly conduct an indepth review of these safety issues.

Mrs. LLOYD. Thank you very much, Bill, and I certainly want to commend you for your leadership and the time that you are putting in on the investigations, and we appreciate all you are doing not only for this committee, but for our Congress.

Sid, we welcome your remarks at this time, the distinguished ranking Republican on the Energy Research and Production Subcommittee. Mr. Sid Morrison.

Mr. MORRISON. Thank you, Madam Chairman. I would like to add my voice in welcome to those witnesses who will be appearing before us in this most significant hearing. I am delighted to have Bill Nelson with us as we look at this aspect of the space program over which our two subcommittees share jurisdiction.

Rather than involve myself with lengthy comments, Madam Chairman, I would like to associate myself both with the comments you and Chairman Nelson have provided, and feel that the shock of the *Challenger* accident forces us to reconsider the worst case scenarios involving RTG's launched on the shuttle. A reexamination of this subject is not only timely, but highly appropriate, and in reexamining these safety issues, we will look at the process used to review the possible dangers.

I think we will find that the process itself contains a number of checks and balances using both independent and agency resources, but it is important, of course, to ensure that each participant in this process carry out appropriate responsibility. So I look forward

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to the hearing, Madam Chairman, and I would ask that Congressman Bob Walker, who serves as the ranking member on the Space Subcommittee, I ask unanimous consent that his opening statement be included as part of the record.

[The prepared opening statement of Mr. Morrison follows:]

OPENING STATEMENT OF HON. SID MORRISON

Good afternoon, I'd like to welcome all of our witnesses today and look forward to their presentations on a most interesting aspect of our space program.

Today we want to examine the process used by NASA, the Department of Energy, and the Department of Defense to analyze the safety of launching Radioisotope Thermoelectric Generators into orbit on the Space Shuttle.

I don't think there is any doubt that RTGs in and of themselves are an essential aspect of our space program, particularly interplanetary missions. The world has been thrilled with the pictures and information relayed back to us from Uranus, and I sense that all Americans are proud of this accomplishment. I also sense that very few know what makes the whole thing go.

There is also little doubt that RTGs in and of themselves are safe. The plutonium power source is encased in iridium, one of the hardest substances known to man. This is, in turn, surrounded by graphite which provides an additional barrier. The fuel modules are prepared to withstand the rigors of atmospheric re-entry and overpressures of up to 2,200 pounds per square inch. More importantly, we have discovered some impacts an RTG cannot withstand. Knowledge of our limitations is just as important as knowing our capabilities.

The shock of the Challenger accident forces us to reconsider the worst case scenarios involving RTGs launched on the Shuttle. This re-examination is not only timely, but appropriate.

In re-examining these safety issues we will look at the process used to review the possible dangers. I think we'll find that the process itself contains many checks and balances, using both independent and agency resources. However, it is important to ensure that each participant carry out appropriate responsibility in the process.

The outcome of this hearing may point to a need for further safety studies of RTGs. We may discover that the review process needs a little fine tuning. Or we may find that the current process is right on target. Regardless of the outcome, it is essential that this only be a pause along the road toward the continued safe exploration of space.

Mrs. LLOYD. Without objection, Mr. Walker's remarks will be made a part of the record.

[The prepared opening statement of Mr. Walker follows:]

OPENING REMARKS OF HON. ROBERT S. WALKER

Good afternoon. Our hearing topic is one that has caused considerable public interest and debate over the years.

Both the United States and the Soviet Union have used Nuclear Power Generators to provide electrical power to spacecraft systems. RTG's are particularly necessary for our planetary exploration missions since it is impossible to generate enough electrical power to supply spacecraft requirements with photovoltaic displays as the distance to the sun gets larger.

The tragic loss of Challenger has again raised questions about what might happen to RTGs in the cargo bay if there were an accident and what the consequences might be if an accident occurred.

This hearing is not an investigation into the Challenger accident. That will be explored by the Committee in considerable depth later this year.

Today we are meeting to examine the process that leads the President to approve RTGs for launch and to determine if all the risks have been identified, properly quantified, and thoroughly understood as the approval process progresses.

I should mention that this committee is unique in that we have the jurisdiction over the research and development activities of DOE in designing and producing the RTGs and in the spaceflight activities of NASA.

Mrs. LLOYD. At this time I also ask unanimous consent that these hearings may be televised and recorded. Without objection, it will be.

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Our first witness today will be Dr. Lyle Wilcox from the Department of Energy. Dr. Wilcox has appeared before this committee on numerous occasions.

Dr. Wilcox, your entire statement will be made a part of the record, and you may summarize or proceed as you wish. I am very happy to have you with us today.

STATEMENT OF DR. LYLE C. WILCOX, DEPUTY ASSISTANT SECRETARY FOR REACTOR SYSTEMS, DEVELOPMENT AND TECHNOLOGY, ACCOMPANIED BY GARY L. BENNETT, DEPUTY DIRECTOR, DIVISION OF SPECIAL APPLICATIONS, DOE; STEPHEN J. LANES, DIRECTOR, OFFICE OF DEFENSE ENERGY PROJECTS AND SPECIAL APPLICATIONS, DOE; AND JAMES J. LOMBARDO, DIRECTOR, DIVISION OF SPECIAL APPLICATIONS, DOE

Dr. WILCOX. Thank you, Madam Chairman, it is my pleasure to be here again.

Mrs. LLOYD. Would you identify the gentlemen that are with you today?

Dr. WILCOX. Yes, I shall. I have with me at the table today, Steve Lanes, Director of our Office of Defense Energy Projects---

Mrs. LLOYD. Certainly Steve is no stranger to this committee. He is a good friend, and we are glad to see you back, Steve.

Mr. LANES. Thank you, Madam Chairman.

Dr. WILCOX. To his right is James Lombardo, Director of our Special Applications Division.

Mrs. LLOYD. Good to have you, Mr. Lombardo.

Dr. WILCOX. To my left, Dr. Gary Bennett, who also is of that special applications staff.

Mrs. LLOYD. Good to have you with us also.

Dr. WILCOX. My colleagues at this point do not have separate statements. I would like to ask your permission to have them help me in addressing and answering the questions.

Mrs. LLOYD. Without objection, that will be a part of the record.

Dr. WILCOX. I request that the formal statement that we previously submitted be included in the hearing record, and I will begin my remarks today by briefly summarizing the Department's role in the development of radioisotope thermoelectric generators, or RTG's.

Since 1961, the United States has used 34 RTG's developed by DOE and its predecessor organizations for electric power in 19 space missions. These include navigation and communications satellites launched by the Department of Defense, and the Nimbus, Apollo, Pioneer, Viking, Voyager spacecraft launched by the National Aeronautics and Space Administration.

RTG's have employed a variety of thermoelectric conversion and radioisotope heat source technologies spanning a power range from a few electrical watts to approximately 300 watts. The data derived from the diverse uses of these nuclear power sources demonstrate the capability of RTG's to function for many years in a variety of space mission environments in a manner that is reliable and safe.

The Department continues to apply its unique experience and technical resources to the effort of design, fabrication, and delivery of isotope power supplies to our customers for both military and ci-

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vilian applications. Our first goal has been to develop the technology base to meet civilian and military requirements for RTG's in present and future space and terrestrial applications. The second goal is to build, develop, and deliver flight-qualified RTG's to support those specific applications.

A recent dramatic application of RTG's was the Voyager 2 fly-by to Uranus, a planet so far from the Sun that it receives less than three-tenths of 1 percent of the sunlight received at Earth. In such a region of dark space, nuclear power is the viable option for planetary explorers. Over 8 years after launch, the RTG's on Voyager 2 are still performing well above prelaunch predictions. Two upcoming NASA interplanetary spacecraft launches, Galileo and Ulysses, will both rely solely upon RTG's for their mission power. The RTG's for these spacecraft will be the general-purpose heat source RTG's rated at 300 electrical watts each.

I would like to discuss the specific elements of the Department's program directed toward these developments. In response to future NASA and DOD space missions, DOE is developing an advanced modular RTG that offers promise of higher power density and greater size adaptability as mission requirements change. This modular isotope thermoelectric generator will enable NASA to accommodate a range of interplanetary missions identified by the Solar System Exploration Commission of the NASA Advisory Council.

These MITG's are also a potential power source for the experimental flight of the boost surveiliance and tracking system for the Strategic Defense Initiative Program. In parallel with MITG development, DOE continues to improve thermoelectric conversion efficiencies, including silicon germanium optimization, electrical contacting, evaluation of materials properties, degradation mechanisms, and material interactions. To respond to future RTG delivery requirements, it is essential that DOE maintain a viable heat source production capability within its laboratory structure and continue those efforts necessary to improve heat source safety, improve production efficiency to reduce heat source costs, and continue work in long-lead technology areas. In addition, the Department will continue to meet its obligations to deliver low wattage RTG's for terrestrial, military missions.

Next, I would like to discuss the safety aspects of our program activities. As with all of the Department's nuclear energy programs, protection of the public health and safety and of the environment is an integral part of the engineering development of these systems.

Every nuclear-fueled power system, which is considered for use in a space application by the United States, undergoes stringent safety reviews. These reviews are undertaken and coordinated by an Interagency Nuclear Safety Review Panel, chaired by three coordinators appointed by the heads of DOD, NASA, and DOE. DOD and NASA personnel are involved because these two agencies have the primary safety responsibility and expertise both as launching organizations and users of space nuclear power. DOE has responsibility for the safety of nuclear space power systems.

The safety process starts during the development phases of the space mission and the nuclear power system that is chosen to satis-

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fy the particular power requirements. The process includes the scheduled issuance of preliminary, updated, and final safety analysis reports prepared by the DOE nuclear power contractor. As a source book for the analyses, DOE uses input data supplied by the mission agency, NASA or DOD, for the mission and spacecraft details, the launch vehicle, postulated accidents, accident probabilities, and the environments that will be imposed upon the nuclear power system. The safety analysis reports are heavily supported by tests that impose the expected mission environments on the RTG and its radioisotope heat source.

DOE's space nuclear safety organizations that contribute to this—I would like to mention briefly—a number of contractors and laboratories are involved in insuring safe performance of RTG's. The responsibilities and the functions of these participants are as follows: General Electric is the systems contractor and as such, is responsible for the design of general purpose heat source radioisotope thermal generators. General Electric is also responsible for performing the safety analysis, preparing the safety analysis reports, and has been closely involved in the safety testing.

Mound plant, operated for DOE by Monsanto Research Corp., prepared the safety analysis report for the lightweight radioisotope heater units. Mound has prepared safety analysis reports for heater units and has the expertise to do this type of analysis. Mound used the same input and probablistic approach that GE used.

The Los Alamos National Laboratory, operated for DOE by the University of California, is the lead safety laboratory for the Radioisotope Safety Program. Los Alamos conducted, or had Sandia conduct, all of the safety verification tests used in support of the GPHS and RTG SAR in most of the tests for the lightweight radioisotope heater unit. These tests included capsule impacts, solid propellent fires, projectile impacts, explosions, and flyer plate impacts.

In addition, Los Alamos conducted an environmental test program to study the behavior of plutonium 238 in the environment. Los Alamos also provides independent technical support to the heat source program.

The Applied Physics Laboratory, operated by Johns Hopkins University, performs independent aerothermal calculations. Particular attention is paid to calculating thermal stresses, ablation, and thermal response of heat source modules during postulated reentries. APL maintains the aerothermal data base and computer codes needed for these calculations.

NUS Corp. provides independent safety analysis and risk assessment. NUS personnel have developed computer models for calculating the meteorological dispersion of radioisotopes and for calculating the associated risk. For the GPHS RTG's and safety assessment report and for the lightweight units, NUS prepared the nuclear-risk analysis document. The safety review process conducted by the various laboratories and contractors covers several levels. The program staff in the DOE Office of Nuclear Energy reviews the SAR's and in parallel with an independent contractor review team and a separate independent review by the DOE Office of Environment, Safety and Health.

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Upon completion of these three reviews, an INSRP team, the interagency nuclear safety review panel team members, conduct a multiagency, independent review prior to issuing their own nuclear risk assessment. This is called a safety evaluation report, or SER. The SER is a key document in deciding whether to support a launch recommendation. The overall safety analysis and risk assessment considers the potential of human exposures to radiation and the probabilities of exposure for all phases of the proposed mission.

In addition to the risks, the potential environmental impact of the mission or series of missions is assessed as an activity separate from risk analysis. Because safety is built into the nuclear power sources from the beginning, the safety review process is an integral part of the overall flight system development.

In conclusion, the unique characteristics of nuclear-powered electric generators; that is, their compact size, lightweight, very high reliability, and very long life, enable operation of the sensing, the analytical, the communication systems of spacecraft, satellites, and other remotely located devices for long times without relying on external sources of energy. Environmentally acceptable, operationally safe, and technically qualified nuclear energy systems are used for Earth-orbital and interplanetary space missions, as well as terrestrial applications. The history of these systems has shown that they can be safely and reliably built to meet a variety of mission objectives.

We believe that RTG's will remain a very strong contender and, in some cases, a mandatory requirement for space missions that require power up to about 1 kilowatt, with high reliability and long mission durations. The advances that have been made in RTG performance, power-to-weight ratios, reliability, and safety to meet NASA and DOD needs would not have been possible without a continuing technology program for the development of new thermoelectric materials, new converter designs, and new heat source designs.

To support such future space missions as the NASA Mariner Mark II and the DOD BSTS Boost series in the early 1990's, we plan to continue RTG technology development on several fronts, including continuation of our efforts to improve the thermoelectric materials; two, the development and demonstration of the technology for a modular RTG; and, three, improvement of the design margin for the general purpose heat source. This heat source will be used not only for the modular RTG for future NASA or DOD missions, but also for a dynamic isotope power source.

The Department's Advanced Nuclear Systems Program has provided essential support to the Nation's Space Program and plans to continue that support. The Department is proud of its past accomplishment and anticipates a growing need for this unique technology in the future.

Mr. Chairman, that completes my statement, and I stand ready to answer questions.

[The prepared statement of Dr. Wilcox follows:]

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STATEMENT OF
DR. LYLE C. WILCOX
DEPUTY ASSISTANT SECRETARY FOR
REACTOR SYSTEMS, DEVELOPMENT AND TECHNOLOGY
U. S. DEPARTMENT OF ENERGY
BEFORE THE
SUBCOMMITTEE ON ENERGY RESEARCH AND PRODUCTION
AND THE
SUBCOMMITTEE ON SPACE SCIENCE AND APPLICATIONS
COMMITTEE ON SCIENCE AND TECHNOLOGY
U. S. HOUSE OF REPRESENTATIVES

MARCH 4, 1986

I am pleased to have the opportunity to discuss the program under which the Department of Energy (DOE) develops, demonstrates, and supplies radioisotope power sources for U.S. civilian and military space and terrestrial applications.

HISTORY AND DOE ROLE

Since 1961, the United States has used 34 radioisotope thermoelectric generators (RTGs), developed by DOE and its predecessor organizations, for electric power in 19 space systems, including navigation and communications satellites launched by the Department of Defense (DOD) and the Nimbus, Apollo, Pioneer, Viking, and Voyager spacecraft launched by the National Aeronautics and Space Administration (NASA). RTGs have employed a variety of thermoelectric conversion and radioisotope heat source technologies spanning a power range from a few electrical watts to approximately 300 watts. The data derived from the diverse uses of these nuclear power sources demonstrate the capability of RTGs to function for many years in a variety of space mission environments in a manner that is reliable and safe.

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The Department continues to apply its unique experience and technical resources to the effort of design, fabrication and delivery of isotope power supplies to our customers for both military and civilian applications. Our first goal has been to develop the technology base to meet civilian and military requirements for RTGs in present and future space and terrestrial applications. The second goal is to build, develop, and deliver flight-qualified RTGs to support those applications.

A recent dramatic application of RTGs was the Voyager 2 fly-by of Uranus--a planet so far from the Sun that it receives less than 0.3 percent of the sunlight received at Earth. In such a region of dark space, nuclear power is the only viable option for planetary explorers. Over 8 years after launch, the RTGs on Voyager 2 are still performing well above prelaunch predictions. Two upcoming NASA interplanetary spacecraft launches (Galileo and Ulysses) will both rely solely upon RTGs for their mission power. The RTGs for these spacecraft will be the General Purpose Heat Source (GPHS) RTGs, rated at 300 electrical watts each.

DOE PROGRAM

In response to future NASA and DOD space missions, DOE is developing an advanced modular RTG that offers promise of higher power density and greater size adaptability as mission requirements change. The Modular Isotope Thermoelectric Generator (MITG) will enable NASA to accommodate a range of interplanetary missions identified by the Solar System Exploration Commission of the NASA Advisory Council. The MITG is also a potential power source for the experimental flight of the Boost Surveillance and

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Tracking System (BSTS) for the Strategic Defense Initiative (SDI) program. In parallel with MITG development, DOE continues to improve thermoelectric conversion efficiencies including silicon germanium optimization, electrical contacting, evaluation of materials properties, degradation mechanisms, and material interactions. To respond to future RTG delivery requirements, it is essential that DOE maintain a viable heat source production capability within its laboratory structure and continue those efforts necessary to improve heat source safety, improve production efficiency to reduce heat source costs, and continue work in long-lead technology areas. In addition, the Department will continue to meet its obligations to deliver low-wattage RTGs for terrestrial military missions.

SAFETY

As with all of the Department's nuclear energy programs, protection of the public health and safety and of the environment is an integral part of the engineering development of these systems.

Every nuclear-fueled power system which is considered for use in a space application by the U.S. undergoes stringent safety reviews. These reviews are undertaken and coordinated by an Interagency Nuclear Safety Review Panel (INSRP), chaired by three coordinators appointed by the heads of DOD, NASA, and DOE. DOD and NASA personnel are involved because these two agencies have the primary safety responsibility and expertise both as launching organizations and users of space nuclear power. DOE has responsibility for the safety of nuclear space power systems.

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The safety process starts during the development phases of the space mission and the nuclear power system that is chosen to satisfy the power requirements. The process includes the scheduled issuance of Preliminary, Updated, and Final Safety Analysis Reports prepared by the DOE nuclear power system contractor. As a source book for the analyses, DOE uses input data supplied by the mission agency, e.g., NASA or DOD, for the mission and spacecraft details, the launch vehicle, postulated accidents, accident probabilities, and the environments that will be imposed upon the nuclear power system. The Safety Analysis Reports (SARs) are heavily supported by tests that impose the expected mission environments on the RTG and its radioisotope heat source.

The safety review process covers many levels. The program staff in the DOE Office of Nuclear Energy reviews the SARs in parallel with an independent contractor review team and a separate, independent review by the DOE Office of Environment, Safety, and Health. Upon completion of these three reviews, INSRP team members conduct a multi-agency, independent review prior to issuing their own nuclear risk assessment, the Safety Evaluation Report (SER). The SER is a key document in deciding whether to support a launch recommendation.

The overall safety analysis and risk assessment considers the potential human exposures to radiation and the probabilities of exposure for all phases of the proposed mission. In addition to the risks, the potential environmental impact of the mission or series of missions is assessed as an activity separate for the risk analysis. Because safety is built into

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these nuclear power sources from the beginning, this safety review process is an integral part of the overall flight system development.

CONCLUSION

The unique characteristics of nuclear-powered electric g[illegible]rors (i.e., compact size, light weight, reliable, and long life) enable operation of the sensing, analytical and communication systems of spacecraft, satellites, and other remotely located devices for long times without relying on external sources of energy. Environmentally acceptable, operationally safe, and technically qualified nuclear energy systems are used for Earth-orbital and interplanetary space missions, as well as terrestrial applications. The history of these systems has shown that they can be safely and reliably built to meet a variety of mission objectives.

We believe that RTGs will remain a very strong contender and, in some cases, a mandatory requirement for space missions that require power up to about one kilowatt, high reliability, and very long mission durations. The advancements that have been made in RTG performance, power-to-weight ratios, reliability, and safety to meet NASA and DOD needs would not have been possible without a continuing technology program for the development of new thermoelectric materials, new converter designs, and new heat source designs. To support such future space missions as the NASA Mariner Mark II and the DOD BSTS series in the early 1990's, we plan to continue RTG technology development on several fronts, including: (1) continuation of our efforts to improve the thermoelectric materials; (2) development and demonstration of the technology for a modular RTG; and (3) improvement of

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the design margin for the General Purpose Heat Source. This heat source will be used not only for the modular RTG for future NASA or DOD missions, but also for a dynamic isotope power system.

The Department's Advanced Nuclear Systems program has provided essential support to the Nation's space program and plans to continue that support, including an expanded effort in support of SDI needs. The Department is proud of its past accomplishment and history in the continued development of space nuclear power, and anticipates a growing need for this unique technology in the future.

This concludes my statement. We would be pleased to respond to your questions at this time.

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U.S. Department of Energy
Assistant Secretary for
Congressional, Intergovernmental
and Public Affairs
Office of Public Affairs
Washington, D.C. 20585
202/252-5644

BIOGRAPHY

LYLE C. WILCOX

Lyle C. Wilcox was appointed Deputy Assistant Secretary for Reactor Systems, Development and Technology, Office of Nuclear Energy, U.S. Department of Energy (DOE) in 1984. In this position, he is responsible for policy formulation in nuclear energy systems and policy guidance for the overall research and development program. He is also responsible for negotiating U.S. positions relative to nuclear energy in the international arena.

Prior to joining DOE, Dr. Wilcox was President of the University of Southern Colorado from 1980 to 1984. His responsibilities included managing the operational resources and personnel of the Institution, including direction of its academic programs at the undergraduate and graduate levels.

In 1966 Dr. Wilcox joined the staff of Clemson University in Clemson, South Carolina, as Head of the Department of Electrical and Computer Engineering; in 1971 was named Associate Dean, College of Engineering; and, from 1973 to 1980 he was the Dean of Engineering.

Dr. Wilcox was an Associate Professor at the University of Arkansas and served concurrently as Chief Engineer and Director of Operations at the Southern Medical Support Center, Veterans Administration, from 1964 to 1966. He was an Instructor to the Assistant Professor in Engineering at Michigan State University from 1958 to 1964.

Widely recognized in his field, Dr. Wilcox has served as adviser, and consultant for organizations such as: the National Science Foundation, S.C. State Department of Education, and the Engineers' Council for Professional Development, National Accreditation Board for Engineering and Technology. He was appointed to the Board of Directors of Parkview Hospital System, Member of the Board of Directors of the Pueblo Economic Development Corporation, Bank Director of the Intrawest Bank, and member of the Council on Technical Manpower Utilization for the Western Interstate Commission for Higher Education.

Dr. Wilcox received his B.S. degree in electrical engineering from Tri-State University in 1954; his M.S. and Ph.D. degrees, also in electrical engineering, from Michigan State University in 1958 and 1963 respectively. Dr. Wilcox has written over 60

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technical publications. His professional activities and memberships include, among others: American Nuclear Society, the American Society for Engineering Education, the Institute of Electrical and Electronic Engineers, Inc., American Management Association and American Association of the Advancement of Science.

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Mrs. LLOYD. Thank you very much, Dr. Wilcox. There are a lot of areas that we could get into, but some of our questions will have to be submitted in writing because we can't cover as broad a range as we would like to today, but I would like to talk to you basically about the methodology that is used to calculate the nuclear risk for the RTG's.

Dr. Wilcox, does this compare favorably to the methods that are used to assess our radiological exposure risk, for instance, in a nuclear powerplant? What are the differences and the similarities in these two methodologies, to give us a better understanding of your assessment?

Dr. WILCOX. The similarities start from the very beginning of the engineering design and development. It starts from a very careful analysis of what kind of environmental conditions—and by environmental, I am talking about conditions that these devices would be exposed to, accident conditions, pressure levels, impacts, that sort of an environment.

We carefully look at what kind of probabilities lead up to creating those kinds of environments, and as you certainly correctly mentioned that at the outset, some have very low probabilities, some have higher probabilities of occurrence, so that is a part of the analysis that we use, the probabilities of what kind of an environment will develop.

Second, we look at the implication that that environment has on the RTG itself. Is it a severe environment or a modest environment? What will the RTG have to withstand in terms of that kind of an environment, and we look at the results of all of these environments and all of these exposure conditions to the RTG. We look at what kind of emperical conditions we need to set up in the laboratories through experimental processes that would simulate these conditions so that these are not all purely analytical studies.

Mrs. LLOYD. It is a more engineering assessment.

Dr. WILCOX. Engineering. We estimate an environment, and then we try to duplicate that environment or simulate that environment, make the test and as accurately as we can record the conditions of the test—pressures, velocities, and so on. Then from there we look at the particular modes that the RTG might go into. Would it go into a failure mode? Would it be perhaps bent or pulled and pushed, or would it be destroyed to some degree?

Mrs. LLOYD. In what phase?

Dr. WILCOX. That would be after we have established the environment and the possible accidental conditions that would occur in that environment. We know what the RTG design looks like at that point, and we combine those two and look at what kind of a failure could occur.

For example, in the RTG we know that we have a heavy aluminum casing around the RTG, first of all, with its heat dissipation fins and so on. We know that we have beneath that structure, the modular structure of the RTG which is——

Mrs. LLOYD. You look more at structure, and NASA would look more at environment; is that correct?

Dr. WILCOX. Yes; that's right. They would tell us what kind of an environment to expect, and we would look at the device and how it

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is going to behave in that environment, and how we would engineer it to withstand these various environments.

Mrs. LLOYD. How would that compare to your assessment of the powerplant?

Dr. WILCOX. The same case. You would look at the safety characteristics of the powerplant and what would need to be added to the powerplant in terms of either engineering components or engineering controls or operator training, and then you would look at the different occurrences of a failure that might happen, what the probability of the failure is, and the consequence of the failure.

At this point you reach what is defined as the source term point where you would have a release of radioactive material. At that point, you look at where it is released, when it is released, the quantity of the release and then you go into the risk analysis studies.

Mrs. LLOYD. Maybe we ought to clarify something for those in the audience. An RTG is not a nuclear powerplant.

Dr. WILCOX. Absolutely not. No, it is radioactive material that generates heat. We capture that heat, and we change that heat directly into electricity. It is not a reactor.

Mrs. LLOYD. Going to another subject, Dr. Wilcox, I would like for you to explain to the committee the intent, as well as the experimental parameters that describe Project Direct Course as it relates to the RTG. Would you elaborate on this project, please?

Dr. WILCOX. Project Direct Course is associated with an experiment that was run in late fall of 1983, I believe, October 1983. That experiment used a detonation or an explosion of a TNT type of explosion to create certain pressure levels, static and dynamic pressure levels, and we used a simulated RTG in that environment close to that explosion, at that point feeling that that would be a reasonable simulation of an accident environment for a space application.

It turns out that that was an incorrect assumption, and I have to clarify that comment by saying that direct course or a TNT-type of explosion is very different from a kind of an explosion that you would have if you had hydrogen-oxygen explosion. The pressure levels are different, and there are factors, including dynamic pressure or peak pressure level that comes into place.

Mrs. LLOYD. There was an indication that this simulant was rather unrealistic.

Dr. WILCOX. Yes, that was not the right environment for testing RTG's as they would be used in space application, and it destroyed the RTG, but that was not a valid test for it. We can go as deeply into that as you like, but we did set up a working group to—independent working group to analyze that experiment. These were experts in explosives to tell us what happened, what the differences are under these different conditions, and they confirmed that this was simply not the scenario to use with a space-based RTG.

Mrs. LLOYD. Thank you. Mr. Morrison.

Mr. MORRISON. Dr. Wilcox, it probably would be helpful to some of us that sort of look at this issue from the outside if someone could analyze very quickly what could go wrong; that is, we have a radioisotope used as you have described, for the generation of energy, and working most effectively, I might add. But we can all

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vividly recall the *Challenger* situation where they were in the Earth's atmosphere very clearly. I presume an RTG on that shuttle would have probably been destroyed as many elements were and been part of the water recovery that we have seen of so many of those parts.

Is that a fair assumption? And there would probably be very little risk of any dissemination of the radioisotope?

Dr. WILCOX. We are speculating again in terms of what would happen, and I would like to be sure that we wait until we get all of the data that is associated with that kind of an accident, but it is, in my judgment, likely that what you have described is probably the consequence of that kind of an accident. But we are going to look very carefully at everything that comes out of that accident in terms of pressure levels, what happens to the components, and use that as our environment that I just described previously. So some of this is speculation, of course, at this point.

Mr. MORRISON. Then let's take the next step, a higher shot, something that actually goes beyond the Earth's atmosphere and I would presume there you would be subject to different pressures and different thermal problems. What, from your design of RTG's, is the protection that is provided under that particular circumstance where there, in essence, would be burnup of more fragile materials?

Dr. WILCOX. The design of the RTG's that we are using are designed to return to Earth intact and not burn up in the atmosphere.

Mr. MORRISON. That was a decision made, what, after 1964 when you had a circumstance?

Dr. WILCOX. Yes.

Mr. MORRISON. Would you share with us why that particular decision was made, why did you decide to bring the materials back intact?

Dr. WILCOX. Bringing them back intact means that with our technology we know where they are going to go. We can find them, locate them and pick them up and recover them and reaccount for that plutonium. If you lose them in the atmosphere and they burn up on the way down, then there is a distribution of the material in the upper atmosphere very, very sparsely in terms of density. But it is always better to simply keep it in a package and pick it up.

Mr. MORRISON. So that was the goal that you could find the source materials as opposed to distributing them.

Dr. WILCOX. Yes.

Mr. MORRISON. OK. Madam Chairman, I have a number of questions. I know you have urged us to do what we can in writing just for the sake of——

Mrs. LLOYD. The bell hasn't gone off, Mr. Morrison.

Mr. MORRISON. OK. One of the things that I was hoping that we would really come up with today was a look at the safety review process, and you have certainly described part of that in your opening testimony. I had some questions, for instance, what is the difference between a safety review analysis, which is prepared by your agency, and a safety evaluation report. I guess what we need to make sure of is that all of these things tie together to reach some conclusions that are appropriate.

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Dr. WILCOX. The safety analysis that is generated, let's say, by many of the folks, the contractors, and the people that I have described in my opening remarks, looks at the test environments, the engineering environments, the design of the RTG and so on, and uses their very best judgment from a lot of different directions and a lot of different areas of expertise, and puts together what we feel is the best safety analysis report and evaluation that we can. But we subject that to further scrutiny within DOE, for example, by our environmental and health group, which is independent from our programmatic office, dealing with RTG's.

They look at it from a different perspective and point of view than, in some cases, we would. After that process is cleared in DOE, then it continues into the organization or the group of individuals that will establish the SER or the Safety Evaluation Report. That is an interagency group that I described previously. So then each of the engineering design decisions, the risk analyses, probabilistic matrix that we use, is all analyzed from three different directions in addition to the initial group that formulated them.

You have to satisfy that whole chain of events before you get any kind of writeoff that would put such a program in the hands, or even suggest that a program would go in the hands of the Office of Science and Technology recommending a launch. There are a lot of independent contractors, a lot of independent reviewers, and a lot of expertise coming from not just engineering and science, but other disciplines as well.

Mr. MORRISON. One last question, if I could, Madam Chairman. Isn't the amount of material we are talking about, infinitesimal, particularly when you compare it with the amount of radioactive material generated by the Sun every day, and introduced into the Earth's atmosphere?

Dr. WILCOX. On that basis, yes. The answer to your question is, yes, very, very small.

Mr. MORRISON. But it is your opinion—and obviously this is a direction that you have gone, that we need to prevent the isotope from being introduced into that environment.

Dr. WILCOX. The goal of everything and anything that we do is to make that risk absolutely as small as possible, and we are not looking for anything other than eliminating all of the possibilities for a failure as we identify them and designing the RTG the best way that mankind knows how to design them to withstand any environment that they might be exposed to. We are not accepting any theoretical lower boundary or anything. We are aiming for the best that can be done.

Mr. MORRISON. Thank you. Thank you, Madam Chairman.

Mrs. LLOYD. Thank you very much, Mr. Morrison.

Mr. Nelson.

Mr. NELSON. Thank you, Madam Chairman.

Dr. Wilcox, what is your best estimate of the blast overpressure that existed during the *Challenger* explosion?

Dr. WILCOX. I would like to defer. Maybe I can get a better estimate from my colleague.

Mr. NELSON. Anyone.

Dr. WILCOX. Jim, would you like to estimate that?

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Mr. LOMBARDO. Mr. Chairman, I can only relate to you information I received from the JPL project which indicated the overpressures on *Challenger* were somewhere between 200 to 400 pounds per square inch.

Mr. NELSON. 200 to 400 pounds per square inch.

Mr. LOMBARDO. That's my best understanding.

Mr. NELSON. All right. What overpressure was the RTG designed to withstand on Galileo and Ulysses?

Dr. WILCOX. 2,200 pounds per square inch.

Mr. NELSON. 2,200 pounds per square inch. All right, so obviously had it—it is your opinion, then, that had it been on *Challenger* during that tragic accident, that it would have withstood that blast overpressure.

Dr. WILCOX. That is one indication that it would have withstood that overpressure. In fairness, we need to look at the other scenario around that kind of an accident. Overpressure is one criteria that is used. We don't stop with that, however. We also look at impact and shrapnel or particles flying about, so that is a factor we would also, in addition to overpressure——

Mr. NELSON. OK, add that factor—impact. What would be the pounds per square inch there, and would its design of 2,200 pounds per square inch—would it had withstood impact.

Mr. LOMBARDO. At the overpressures that I stated, the velocity of the clads that would be projected into a bulkhead would probably be——

Mr. NELSON. Pull that mike closer to you, please.

Mr. LOMBARDO. At the overpressures that I stated, the velocity of the clads would probably be at a threshold below which they would have impacted on the shuttle bay or shuttle bulkhead. There is, of course, a concern about fragments generated in the explosion itself. We don't have a good idea of what the magnitude or the velocity of those fragments are at this time. We certainly will be looking at that, and as Dr. Wilcox said, a thorough investigation will be made of that *Challenger* accident, and from that investigation, we will be able to answer the question more firmly on whether the RTG would have survived or not.

Mr. NELSON. OK, for the purpose of this hearing, can you give me some numbers of what you know now with regard to impact?

Mr. LOMBARDO. I would say in a speculative way that in my opinion that the RTG would have survived, and you would have picked it up at the bottom of the ocean.

Mr. NELSON. All right, so impact, you are talking impact into the water.

Mr. LOMBARDO. Impact either of fragment from the shuttle or to the shuttle bay or to the shuttle construction, hitting the RTG and opening it up and damaging a clad. The clad is the iridium capsule which encapsulates the fuel. That's a possibility. Also from the overpressure, per se, the RTG could be stripped of the graphite and the clad impacted on some solid structure.

We have looked at all of these activities and we know the threshold damage of the clad under this environment—as soon as we define the environment more firmly, we will be able to answer that question more positively.

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Mr. NELSON. All right, well I am sure you have defined the environment in a scenario in which there might be an explosion on the pad, and there is collision between the RTG and the steel of the launch tower. What is your answer to that?

Mr. LOMBARDO. Well, we have to be specific. We are referring to the *Challenger*. Unfortunately, the *Challenger* explosion or fireball, more correctly, occurred around 78 seconds into flight.

Mr. NELSON. Seventy-four.

Mr. LOMBARDO. Yes, sir. That would mean that the *Challenger* accident occurred well away from the launch complex.

Mr. NELSON. That's correct. I understand that about *Challenger*. I am asking you in your analysis of your design of the RTG, certainly you looked at the scenario of an explosion on the pad. I am not talking about *Challenger*.

Mr. LOMBARDO. Yes; we have.

Mr. NELSON. All right, what is your answer?

Mr. LOMBARDO. There would have been a release in the case of the Ulysses or Galileo type mission. We have analyzed that; it is in our SER, and we have discussed the consequences of such a release.

Mr. NELSON. What is your answer?

Mr. LOMBARDO. There would have been on the pad what we call phase 1, which is the phase which starts from 0 seconds to 1'28 seconds, a release of some plutonium in the launch pad area.

Mr. NELSON. By the collision with the steel launch tower.

Mr. LOMBARDO. And by fragments or impact on concrete, which is also around the launch pad.

Mr. NELSON. All right, when the NASA witness comes up, one of the things I am going to ask them, which you all, I would not expect to answer is, by virtue of adding the Centaur upper stage to the cargo bay, what additional blast overpressure would be caused there as measured against the design of the RTG of withstanding 2,200 pounds per square inch? So if Dr. Silveira would make note of that.

Now, let me ask you—we had some reports on this thing. We had—this is called the Teledyne report. What is the Department of Energy's assessment of this Teledyne reliability analysis? And maybe while you are commenting on that, there was a followup report, which is called the Sandia report, which analyzed further this report.

What is, Dr. Wilcox, DOE's opinion on these reports?

Dr. WILCOX. Of course we received those reports, looked at them, transferred them to NASA with the statement that how is this going to affect the environments that we are going to have to use in exposing the RTG's to. And I would like to ask Gary Bennett, who has looked at this, if he would say specifically how these reports affected our program and particularly how they might have affected the probablities that were associated with our analysis.

Dr. BENNETT. Well, the Teledyne report was a review of an earlier document put out by NASA. Of course, we are not the experts on the space shuttle, so we transmitted these to NASA and requested a review of it. Of course they can speak on this, and they did form a group which looked into the whole issue of probabilities and environments and so forth, and they eventually issued something that we call a Shuttle Data Book.

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are extremely slim, but if you had to design it to that, what would you do so that it would withstand that kind of collision?

Dr. WILCOX. The engineering fixes to that would be to place lighter materials, cushion that impact, and strengthen the structural components of the module that is held together. I think what you are getting at there is first the probability of that occurring is low, so the risk is low associated with it. But assuming that it could happen, what would the RTG look like? And if you directed all of your attention there, again you may have one that you couldn't fly or that you could not build or could not design.

Mr. NELSON. Thank you.

Mrs. LLOYD. Thank you very much, Mr. Nelson. Mr. Walker.

Mr. Walker, we made note, and your opening remarks have been made part of the record.

Mr. Walker is the ranking Republican on the Space Subcommittee, and we are happy to have you here today.

Mr. WALKER. Thank you, Madam Chairman.

Dr. Wilcox, we have had one of these RTG's in a satellite that exploded; isn't that correct?

Dr. WILCOX. That's true.

Mr. WALKER. What was the result of that particular explosion?

Dr. WILCOX. The release was to the atmosphere. It was distributed, was burned up coming down into the atmosphere, and was distributed.

Mr. WALKER. That was the one in 1964 where one burned up in reentry.

Dr. WILCOX. Yes; that's right.

Mr. WALKER. But didn't we also have in 1968 a situation where we actually had a satellite on board a craft that was intentionally destroyed, and so therefore we have with one of these RTG's—had an actual explosion in flight?

Dr. WILCOX. Yes, excuse me. That was the SNAP RTG. That one was aboard at launch. That one was successfully recovered.

Mr. WALKER. And that one was recovered in tact.

Dr. WILCOX. That's right.

Mr. WALKER. What about the RTG that was on Apollo 13?

Dr. WILCOX. This was our SNAP 27 RTG. This was aborted on the way to the Moon. This returned to the South Pacific Ocean intact, and resides there.

Mr. WALKER. So that our experience thus far has been that regardless of probabilities we do have some experience at this point with dealing with explosions of spacecraft and in the case of the actual explosion, we did, in fact, recover the RTG in tact.

Now, if I am understanding the testimony that you have given us thus far, we have had considerable improvements in the safety of the vehicles since the time of those particular incidents; is that correct?

Dr. WILCOX. That's true, and improvements in the design of the RTG's, yes.

Mr. WALKER. So that from actual experience we do have at least some base upon which to draw. Now, I am concerned if you put that against the testimony we heard here a few moments ago about the chance for release of plutonium on the pad if in fact you had an explosion where it struck the pad, what is the difference in that

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It has a much longer title, but they did issue a report which had the environments in it, and the probabilities that we could use in preparing the final safety analysis report.

Mr. NELSON. I still don't understand your answer. Do you attach credence to Teledyne or Sandia or both? What is your opinion.

Dr. BENNETT. The reports got into areas which were out of our expertise. They got into questions on the reliability of different aspects of the shuttle, and we went to the people who were knowledgeable about that and asked for a review of it, and they did issue a document which considered all of these items, and we used it in preparing our safety analysis report.

Mr. NELSON. OK, I will ask that of the NASA witnesses, then, with regard to the question of the failure rate on the shuttle.

Is there anything in your opinion that could be done to make the RTG safer under the scenarios that you have just outlined?

Dr. WILCOX. I think that is a continuing question that we ask, and I think that there is the boundary that you reach in terms of how large can it be, how heavy can it be, and can it still propagate its energy? There are engineering limitations to that. Clearly you can't imbed it in lead or concrete or what not, but I think that underlies all of the engineering that we do.

Why do we put it in iridium? Why do we put a carbon module around it? Why do we pack them densely and then put an encasement around it, and if the question could be answered, do we think we could make the aluminum just a little bit larger, thicker or of different material, and we feel that would make them safer, we would do it. We would design them that way. But there is no obvious correction that I could tell you today that we would make.

Mr. NELSON. Dr. Wilcox, how many additional pounds per square inch would you have to design the RTG for to withstand a collision with the launch tower?

Dr. WILCOX. I think I need to explain pounds per square inch or static pounds per square inch is one criteria that we use. That is taking the module and just hitting it with a terrific blast of air, extremely large pressure. But we are also looking carefully at the secondary effects and tertiary effects of pressure itself is not enough for us. We are wondering what happens if it gets hit by a small piece of metal, or it hits a piece of metal.

Those are tests that we have been running, and you can hear about them in great detail later, if you would like. That allows us to predict probabilities of failure beyond just that pressure level. So I could answer your question by saying that I could go up in peak pressure/static pressure levels, but that isn't really what we are trying to do. Instead of going higher there, we are trying to make this RTG and this assembly also immune to hitting something or something hitting it. And those are experimental environments that we have created and we have run in those directions with peak velocities of particles and materials.

Mr. NELSON. OK, if you don't do it by just increasing your psi, then what do you do assuming that we have an analysis that says—and I am not sure that we do because the probabilities of the explosion occurring on the pad, and this thing suddenly striking the launch tower, those probabilities, I'm sure somebody would say,

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explosion from the one which took place in 1968 where we recovered the RTG in tact?

Mr. LOMBARDO. Mr. Walker, the answer to that briefly is as follows: The explosion that we experienced a few years ago occurred on a vehicle which the RTG was not close to the center of the explosion. We are predicting, and we have analyzed and understand the effect of what would happen on the Ulysses or Galileo mission. The Centaur is inside the shuttle bay right close to the RTG. They are 15 feet away from the center of explosion. It is the Centaur explosion that we have to protect against, and that is a much higher and more difficult problem than we had back the years before.

To answer your question, we have improved the RTG. We have made major strides in the safety aspects, but we now have an environment which is a little more serious than we had before.

Mr. WALKER. I think that is a good explanation. Now, tell me what your conclusions were about the effects of that release of plutonium as a result of the explosion of the RTG on the pad?

Mr. LOMBARDO. From the standpoint of human risk or——

Mr. WALKER. Yes, of human risk and also the damage that it would cause to the pad, the long-term damage that it would cause to the pad.

Mr. LOMBARDO. I hesitate to say this, but to give you the information on risk to an individual, that would have to come in the closed session,[1] which is following this meeting. I don't mean to put you off.

Mr. WALKER. No, that's fine.

Mr. LOMBARDO. As for cleanup, I think that would depend on the severity of the incident, and where it occurred. If it occurred right at the pad, we may be able to clean up an area rather easily. We have a contingency plan which is worked between NASA, the Department of Energy, and the Department of Defense that reacts to these kinds of accidents and takes the appropriate measures to clear up or clean up and prevent people having a high risk by access to contaminated areas.

So to answer your question, it could present a significant problem or it could present a very minor problem, and that depends on the magnitude of the release and also the area of the release; whether it is widespread or confined in a small area.

Mr. WALKER. And in either case, we are talking here about that which you analyzed as being your worst case scenario; is that correct?

Mr. LOMBARDO. Yes, sir, we look at our situation. We determine maximum release cases for our contingency planning.

Mr. WALKER. And can you give us some idea as to what your probability ratio was for a worst case scenario taking place?

Mr. LOMBARDO. I would say it is at least 2 or 3 orders of magnitude below the average, which is somewhere about 10 to the minus 5, so you might be talking about 10 to the minus 8, 9, or 10, a very rare possibility.

Mr. WALKER. Thank you, Madam Chairman.

Mrs. LLOYD. Mr. Fawell.

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[1] Information subsequently declassified; see p. 147.

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Mr. FAWELL. I'm not sure if I followed some of the questions there that Representative Walker was putting to you, but am I correct in assuming that if we took the hypothetical of a potential explosion on the pad along with the facts as outlined by Representative Nelson, that in terms of the potential effect upon the area, assuming the *Challenger* scenario, you would prefer to give that testimony in closed session; is that correct?

What I am trying to found out is what would, taking the hypothetical of the *Challenger* scenario, what would have been the effect if there had been a release of plutonium?

Mr. LOMBARDO. Mr. Fawell.

Mr. FAWELL. Fawell.

Mr. LOMBARDO. I'm sorry. I would like to clear up a point. The point I would like to clear up is if we had a *Challenger* type accident, and if the Centaur is not present in the shuttle bay, we have stated that that particular accident on the pad or in space would have resulted in no release, in our opinion now, based on the inputs we have and our understanding of the overpressures, the *Challenger*-type accident without the Centaur would not have presented us a problem at all.

Mr. FAWELL. I don't mean the *Challenger*. I would take the hypothetical facts—I'm talking about an explosion on the pad. And I am not sure completely what the Centaur is, but I assume that Centaur is there, too. You said there would be a release on the ground then.

Mr. LOMBARDO. When we say there will be the release, I would like to say there may be a release. There are probabilities that should be attached to that statement. There are probabilities that say—the major probabilities there will not be a release, there won't be an accident. However, if there is an accident, there is a probability of some contamination around the pad.

Mr. FAWELL. My question is, then, assuming the release of plutonium under those circumstances on the pad with the scenario of the *Challenger* pad and viewers and population, et cetera, what would be the effect upon the people in general?

Mr. LOMBARDO. It would be a minor effect. The actual numbers, I beg again, will tell you our best estimate of that number, how it might affect people, but at this point that is a classified number.

Mr. NELSON. Would the gentleman yield? Since he said he will share that with you in a classified session——

Mr. FAWELL. I didn't understand that.

Mr. NELSON. Let me just ask one follow-up specifically on that point. You are asking what is it about a scenario of an explosion on the pad. As I understand it, you said the probabilities are 1 in 10 million is what you are talking about.

Mr. LOMBARDO. In the case of a maximum release, that was the question that was asked by the gentlemen—I say in that case, when you are talking about maximum release, you are talking about a highly improbably situation.

Mr. NELSON. And that is 1 in 10 million.

Mr. LOMBARDO. One in about that much.

Mr. NELSON. OK, thank you. Thank you, for yielding.

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Mr. FAWELL. Do you feel that there are sufficient funds budgeted in order for the proper risk analyses to be made considering what has occurred in the *Challenger* scenario.

Dr. WILCOX. I would like to have, if you don't mind, have Steve Lanes—he directs this entire program and I think you can put that question in the context of the entire development program, including safety testing for our RTG Program.

Mr. LANES. Mr. Fawell, we, of course, did not budget for additional analyses in fiscal years 1986 or 1987, and in anticipation of the event that occurred. Now that it has occurred, we are looking at those additional tasks and analyses that we will have to conduct. For example, we will have to ship the RTG's back from the Kennedy Space Center to storage at Mound, and eventually reship them again to Kennedy if the launch should occur next year. So there are a number of tasks that we are going to have to do that had not been previously anticipated.

Those will include revising the safety analysis report again after all the analyses of the accident and the resulting overpressures are assessed, and we do have some activities planned that will relate to those new analyses. There will be many new analyses that we had not previously planned to do. We hope to be able to do them within our current budget for fiscal years 1986 and 1987. We have that matter under assessment now, and we will probably report to the committee at some future time if we feel that we cannot conduct all the additional work we would like to do within the current budget.

Mr. FAWELL. Can I have one more question, Madam Chairman, or have I taken up my time?

Mrs. LLOYD. You may ask one other question.

Mr. FAWELL. This is an elementary question, but we have a plutonium dependent power source here. Are there other energy storage systems available or in the near term available other than the plutonium dependent power source that we are talking about?

Dr. WILCOX. When you are after the kind of long life that we are talking about, numbers of years—8 years, 10 years beyond—when you are after the kind of light weight devices and high efficiency, when you are after the reliability, I don't see any alternatives—reasonable alternatives to this type of a heat source.

Mr. FAWELL. Thank you.

Mrs. LLOYD. Thank you very much, Mr. Fawell.

One question for you, Steve, would you give us some sort of an idea on the kind of money that we have been spending on our safety analysis recently?

Mr. LANES. Madam Chairman, our budget for the last several years has been about the $20 million level, as you know, for the entire advanced nuclear systems program. Part of that goes for design activities, development, launch support and so on. Off the top of my head, I would guess that about one-quarter of that amount goes into direct safety-related analyses and tests.

Mrs. LLOYD. Do you agree on that?

Mr. Walker.

Mr. WALKER. I just wanted to ask one additional question, then, if I might, too.

Mrs. LLOYD. Please.

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Mr. WALKER. Thank you.

If I understood correctly, a few minutes ago you said that the probabilities connected with the explosion on the pad were very much related to the Centaur in close proximity to the RTG. When we arrive at that time that we can fly separately the RTG and the Centaur; namely, when we get a space station, they would be able to assemble the vehicle at the space station. In large part, then, the probabilities would go way down of the kind of situation that you referred to?

Mr. LOMBARDO. Certainly on-pad problems would be nonexistant. Ascent problems would be nonexistant. You might have some orbital explosions that could take place, but the risks to humans is a very minor thing, so the answer to your question, Mr. Walker, yes. that would reduce the problem significantly.

Mrs. LLOYD. To followup on that, if the probability for an accident occurred in the bay, if it is reassembled or assembled in the space station, wouldn't this same probability occur at that time also?

Mr. LOMBARDO. Madam Chairman, you are absolutely correct, and I made a statement saying in orbit accidents could and may occur.

Mrs. LLOYD. Isn't that the most probable scenario?

Mr. LOMBARDO. Yes; we could have an accident occurring on a space station in orbit, but that accident would be very much different—the effects of that accident would be very much different than an on-pad or ascent accident because you are in a high altitude.

Mrs. LLOYD. Because it is spread over a larger area.

Mr. LOMBARDO. You are in a higher altitude, and the plutonium is spread over a wider area.

Mrs. LLOYD. Greater disbursement of the plutonium.

Thank you very much. Thank you, gentlemen, for your testimony and do expect some questions in writing, because I think we have just begun.

Our next witnesses are Dr. Milton Silveira and Mr. Samuel W. Keller. They are here representing the National Aeronautics and Space Administration, and I would like to recognize Dr. Silveira first. Dr. Silveira, we have your statement. You may proceed as you wish. You may summarize, and your entire statement will be made a part of the record.

STATEMENTS OF DR. MILTON A. SILVEIRA, CHIEF ENGINEER, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION AND SAMUEL W. KELLER, DEPUTY OFFICE OF SPACE SCIENCE AND APPLICATIONS, NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Dr. SILVEIRA. Thank you, Madam Chairwoman.

Madam Chairwoman and Mr. Chairman, distinguished members of the subcommittee. I have been asked to discuss a procedure that we basically follow to obtain the approval to fly an RTG. I want to thank you for the opportunity today to be able to come to this committee and present that information.

The RTG safety assessment process is established by a Presidential directive, and it is NSC-25, which is titled the Scientific or

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Technological Experiments with Possible Large Scale Adverse Environmental Effects and Launch of Nuclear Systems into Space. It specifies launch approval by the President or by his delegation to the Director of the Office of Science and Technology Policy, OSTP.

The directive also establishes an independent review panel, which is known as the Interagency Nuclear Safety Review Panel, or commonly referred to as INSRP, which is composed of three coordinators to operate independent of their agency—one from NASA, one from DOE, and one from DOD. The INSRP also has assigned to it and uses several subpanels to assist in their review.

NASA's primary role in the process is to define the potential catastrophic accident scenarios, probabilities and environments associated with the launch vehicle that could threaten the RTG. This data is provided to DOE, Department of Energy, for the preparation of a series of reports.

First, a preliminary safety analysis report, PSAR, that is usually completed about the time that the power system design concept is established. An update to that, the updated safety analysis report, which is usually completed after the design is frozen, and then a final or FSAR, which is a final safety analysis report that is usually completed 1 year prior to the launch.

In parallel to this ongoing NASA/DOE assessment of the risk, INSRP conducts an independent review of the risk utilizing documentation described above, as well as input from the subpanels, contracted data and other sources. Based on the above, the report that is actually used for flight approval is the Safety Evaluation Report [SER] is prepared by INSRP. It is important to understand that the FSAR, which is prepared by DOE is not the basis for launch approval, but is actually the report prepared by the INSRP.

The SER is provided to the NASA Administrator by INSRP. After coordination of the SER with DOD and DOE and inside NASA, the Administrator forwards that to OSTP for the basis of the launch decision by the President or OSTP, as he so chooses. Our basic input, again, is defined in the JSC document, 08116, which is the Space Shuttle Data for Planetary Mission Radioisotope Thermoelectrical Generator Safety Analysis. This document is under formal control. It is developed by an assessment team that consists of the people who designed the vehicle and are responsible for the vehicle's systems and uses the best knowledge base that we know, as far as the launch vehicle hardware is concerned.

The document was coordinated throughout NASA, DOE, and INSRP. It was reviewed and approved by the level II program office. It is actually controlled by that change control board. Any changes to the document have to go through the standard change procedure that we use to make vehicle changes. It also has been reviewed by the associated administrator for space flight and by myself as NASA's chief engineer prior to the release of the document.

NASA's methodology for estimating failure modes and probabilities is discussed in detail in the chapter 3 of that document which I understand your staff and you have a copy of already.

Mrs. LLOYD. We do have a copy.

Dr. SILVEIRA. The methodology is greatly influenced by the fact that earlier in our program it was decided not to use reliability

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numbers or probability numbers in the design of the shuttle program. Our experience particularly in the Apollo Program had indicated that these numbers, because of the experience base, you would find your statistical analysis on was limited. As a matter of fact, it is a matter of interest in the statistical analysis, if you had performed a certain event 1,000 times successfully, you would do a statistical analysis using that data base, you would still only say that you would have the—you would still have the probability of 3 failures in 1,000 events, and that would only be with a 95-percent confidence level, so we feel that using probability numbers, because of the sample base that you can use, are very, very pessimistic.

What we do in our estimating, rather than coming through the data base, we go into looking at the system designs mainly to look at in the estimation of the responsible subsystem managers, to look at what limited data they may have, to look at understanding what numbers they would asses in coming up with a reliability number, and those are the probability numbers that we include in our space shuttle data book for the planetary missions, the document that we talked about before.

The primary tool that our people also use is the failure mode and effect analysis. This is a procedure that we use that goes through and attempts to analyze in worst case, the what if failure modes. After this analysis is done, an additional list, a critical items list that we have heard a lot about recently is prepared and is derived from the FMEA and consists of those single-point failures and/or a redundant element in a life or mission essential application where the redundant element is not capable of check out during the normal mission turnaround sequence, or the loss of a redundant element is not readily detectable by the flight or ground crew, or all redundant elements can be lost by a single credible cause or event such as a contamination or explosion.

It is the consensus of the National Space Transportation System that the approach of determining when a vehicle is safe to fly based on a well-evaluated analytical program with attention to detail is superior to depending on reliability numbers derived from an insufficient data base in which only minimum confidence levels can be established for its flight and ground hardware and software. The NSTS policy requires that corrective action be taken to preclude or minimize recurrence of any failure previously experienced, essentially invalidates any existing statistical data base applicable to that failure. In other words, if we do have a failure, we go back and redesign and improve upon that design, and hopefully make it more reliable than we started out with. It actually destroys the statistical data base that you have.

We feel that the DOE and the INSRP have historically utilized the quantitative approach to the RTG risk assessment, and therefore NASA was asked to develop a quantitative approach to derive probabilities of failure to support their analysis, because all known failures are corrected and failure probability estimates must utilize application of engineering judgment. The approach to establishing these accident failure probabilities involve the following things: Identifying the shuttle failure modes that may lead to a final effect; identifying and evaluating each failure mode for each applicable mission phase; determine intermediate effects; listing applicable components associated with the failure mode; listing the related

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hazards and closure status; identifying applicable critical items list items and their criteria; researching the failure history for each identified component; identifying related turnaround checkout requirements; determining the life limitation for each component; determining redundancy or work-arounds in the design; adding any clarifying remarks and conclusions; and assigning a confidence level based on the assessment.

The failure modes and probabilities for the Centaur used a Centaur data base applied to Galileo/Ulysses missions and engineering judgment to modify that data base.

To go back and indicate what was actually going on, the final failure safety analysis report was completed on October 25, 1985, and was updated on the 17th of December. The tight schedule was primarily due to a review of the updated safety analysis report in June 1984, where the interagency nuclear safety panel, INSRP, took exception to some of the areas and NASA and INSRP questioned some of the reasonableness of many of the accident scenarios, probabilities, and environment.

We asked the Johnson Space Center at that time to prepare an updated or more accurate shuttle data handbook for nuclear launches which was the one that was actually put under that program's change control. During that time DOE also redefined a test program to obtain a better understanding of the survivability of the RTG. That effort produced a more correct and in-depth review of the risk, went into a number of refinements in looking at actually how the failure modes would affect the RTG.

INSRP's safety evaluation report was to be completed in early February and presented to the NASA Administrator on February 18. A meeting was scheduled for the 19th of February for the consideration of any new data by INSRP. Coordination in NASA, DOE, and DOD, any updates were to have been completed by the 10th of March. After these reviews, NASA would have forwarded a request for launch approval to OSTP by March 14.

From our current vantage point there are certainly improvements that can and should be made in the analyses, and I am sure that we will reconsider our position on certain areas after we better understand the causes of the STS 51-L tragedy. Depending on what we learn from this accident, we may consider modifications to some of the probabilities for the RTG mission, even looking at if there are any design improvements that can be made to this system. However, I still believe that a combination of the analytical techniques we used for minimizing the risk is still superior to any numerical analysis approach.

I believe the FSAR produced a conservative estimate of the risk. However, I believe for the most part where these differences of opinion exist, INSRP elected to use the conservative approach as you should in any safety analysis, and would have produced a more conservative assessment of the risk than the FSAR. The schedule did not permit a restructuring of management organizational approaches prior to this mission. However, since the Galileo and Ulysses missions have been delayed, we plan to begin discussions with DOD, DOE, and OSTP in the near future on now we may proceed and improve on that procedure.

Thank you very much.

[The prepared statement of Dr. Silveira follows:]

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Statement of

Dr. Milton A. Silveira
Chief Engineer

National Aeronautics and Space Administration

before the

Subcommittee on Energy Research and Production
and Subcommittee on Space Science and Applications
Committee on Science and Technology
United States House of Representatives

Madam Chairwoman and Distinguished Members of the Subcommittee:

The Radioisotope Thermoelectric Generator (RTG) safety assessment process is established by Presidential Directive/NSC-25, Scientific or Technological Experiments with Possible Large Scale Adverse Environmental Effects and Launch of Nuclear Systems into Space. It specifies launch approval by the President or Director, Office of Science and Technology Policy (OSTP). It establishes an Interagency Nuclear Safety Review Panel (INSRP) composed of three coordinators (NASA, DOE, and DOD). The INSRP also has several subpanels to assist in their review.

NASA's primary role in the process is to define the potential catastrophic accident scenarios, probabilities, and environments associated with the launch vehicle that could threaten the RTG's. This data is provided as input to the Department of Energy (DOE) for the purpose of preparing a Preliminary Safety Analysis Report (PSAR) (usually completed shortly after power system design concept), an Updated Safety Analysis Report (USAR) (usually completed shortly after power system design freeze), and a Final Safety Analysis Report (FSAR) (usually completed about one year before launch). In parallel with this on-going NASA/DOE assessment of the risk, INSRP conducts an independent review of the risk, utilizing the documentation described above as well as input from their subpanels, contractor data, and other sources.

Based on the above, INSRP prepares a Safety Evaluation Report (SER) which serves as the basis for the launch approval request. It is important to understand that the FSAR (prepared by DOE) is not the basis for launch approval; it is the SER (prepared by INSRP). The SER is provided to the NASA Administrator by INSRP. After coordination of the SER with DOD and DOE, and inside NASA, it is forwarded to OSTP by the NASA Administrator and serves as the basis for a launch decision by the President or OSTP.

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NASA's basic input to the process is defined by JSC 08116, Space Shuttle Data for Planetary Mission Radioisotope Thermoelectric Generator (RTG) Safety Analyses. The document is under formal change control procedures. The document was developed by an assessment team composed of system and subsystem personnel from several centers most knowledgeable of the launch vehicle hardware. The document was coordinated throughout NASA, DOE, and INSRP. It was reviewed and approved by the Level II Program Requirements Control Board. It was also reviewed by the Associate Administrator for Space Flight and NASA's Chief Engineer prior to release of the document.

NASA's methodology for estimating failure modes and probabilities, is discussed in detail in Chapter 3 of JSC 08116, a copy of which I understand you already have. This methodology was greatly influenced by the fact that early in the program it was decided not to use reliability (or probability) numbers in the design of the Shuttle program.

In investigating the possible use of numerics on earlier manned spaceflight programs, the use of standard failure rate data was considered and discarded. The primary reasons were:

1) a very small data base of failure rates in the space environment

2) the unknowns of the operating environment itself

3) the discipline of failure analyses and corrective action which were focused to prevent recurrence of the failure made generic failure rate data unusable

4) operating time records which would be required dictated an elaborate "success time" collection system.

In lieu of using probability numbers, the National Space Transportation System (NSTS) relied on a combination of disciplined analytical techniques. The primary tool was Failure Modes and Effects Analysis (FMEA) which is a worst case "what if" analysis of all possible failure modes and their potential worst case effects. In addition, a Critical Items List (CIL) is prepared which is derived from the FMEA and consists of those single failure points and/or a redundant element in a life or mission essential application where; a) The redundant elements are not capable of check-out during the normal mission turnaround sequence, or b) Loss of a redundant element is not readily detectable by the flight or ground crew, or c) All redundant elements can be lost by a single credible cause or event such as contamination or explosion.

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It is the consensus of the NSTS that the approach of determining when a vehicle is safe to fly based on a well-evaluated analytical program with attention to details is superior to depending on a reliability number derived from an insufficient data base in which only minimum confidence levels can be established for its flight and ground hardware and software. NSTS policy, requiring that corrective action be taken to preclude or minimize recurrence of any failure previously experienced, essentially invalidates any existing statistical data base applicable to that failure; this is true because the corrective action entails changing a design, process, or procedure, thus making even statistical data pooling inapplicable.

However, DOE and INSRP have historically utilized a quantitative approach to RTG risk assessments, and therefore NASA had to develop a qualitiative approach to derive probabilities of failure to support their analyses. Because all known failures are corrected, the failure probability estimates must utilize application of engineering judgment. The approach to establishing accident/failure probabilities involved:

1. Identifying shuttle failure modes that may lead to the final effect.
2. Identifying and evaluating each failure mode for each applicable mission phase.
3. Determining intermediate effects.
4. Listing applicable components associated with the failure mode.
5. Listing the related hazards and closure status.
6. Identifying applicable CIL items and their criticality.
7. Researching the failure history for each identified component.
8. Identifying related turnaround checkout requirements.
9. Determining the life limitation for each component.
10. Determining redundancy or work arounds in the design.
11. Adding any clarifying remarks and conclusions.
12. Assigning a confidence level based on the assessment.

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The failure modes and probabilities for the Centaur used a Centaur Data Base applied to Galileo/Ulysses Missions and engineering judgment to modify that data base.

The schedule was tight for many aspects of the mission, including preparation of the safety analysis. The Final Safety Analysis Report (FSAR) was completed on October 25, 1985 and updated on December 17, 1985. The tight schedule was primarily due to a review of the Updated Safety Analyses Report in July, 1984 where the Interagency Nuclear Safety Review Panel (INSRP) took exception to some areas, and NASA and INSRP questioned the reasonableness of many of the accident scenarios, probabilities, and environments. The Johnson Space Center was asked to thoroughly review the Shuttle Data Handbook for nuclear launches, and they made a detailed revision of that document as discussed above. DOE also redefined their test program to obtain a better understanding of the survivability of the Radioisotope Thermoelectric Generators (RTG). The effort produced a much more correct and in-depth review of the risk, but created real schedule problems in resolving technical differences with INSRP. INSRP basically performed a parallel review of the NASA/DOE assessment, developing their own independent positions on the various aspects of the assessment. INSRP's Safety Evaluation Report (SER) was to be completed in early February and presented to the NASA Administrator on February 18, 1986. A meeting was scheduled for February 19, 1986 for consideration of any new data by INSRP. Coordination in NASA, DOE, and DOD, and any updates were to have been completed by March 10, 1986. After these reviews NASA would have forwarded a request for launch approval to OSTP by March 14, 1986.

From our current vantage point there are certainly improvements that can and should be made in the analyses, and I am sure that we will reconsider our position on certain areas after we understand the causes of the STS 51-L accident. Depending on what we learn from this accident, we may consider modifications to some of the probabilites for RTG missions. However, I still believe that the combination of analytical techniques we use for minimizing risk is superior to a numerical approach.

Although I believe the FSAR produced a conservative estimate of the risk, I also believe there are inherent problems in the review process. The management/organizational structure is complex and not well defined, probably because we have not been through this process since the Voyager Mission in 1977. Also, the fact that this was to be the first launch of an RTG on the STS created problems that were not recognized early. It created delays in the assessment and resulted in divergent positions on technical issues. However, I believe, for the most part, where these differences of opinion existed, INSRP elected to use the

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conservative approach and would have produced a more conservative assessment of the risk than the FSAR. The schedule did not permit a restructuring of the management/organizational approach prior to the missions. Since Galileo and Ulysses will be delayed, we plan to begin discussions with DOD, DOE and OSTP in the near future on how the process might be improved.

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Mrs. LLOYD. Thank you very much, Dr. Silveira. You commented that the probabilistic numbers were pessimistic. Now, in what frame did you use the word, "pessimistic?" Pessimistic in accuracy or that you felt that the pessimistic report might do harm to the program?

Dr. SILVEIRA. From this aspect: as I try to cite an example, if indeed a certain event had occurred successfully 1,000 times, if you went through a statistical analysis and determined a probability from that, it would say in the next 1,000 occurrences you would have 3 failures. We think that that is pessimistic as far as having demonstrated it at least 1,000 successful events.

Mrs. LLOYD. Then you felt that it was not accurately——

Dr. SILVEIRA. We thought that by using a technical rationale in looking at the design and seeing where the failures were, that we could better come at what the probability of failure was from that direction.

Mrs. LLOYD. Obviously this is an analytical evaluation versus a numerical evaluation.

Dr. Silveira, sometime in the Galileo/Ulysses Program, or any other program, it was recognized that NASA had to obtain probability numbers for potential failure modes of the shuttle spacecraft in order that the Department of Energy could perform their necessary nuclear risk analysis for the RTG systems. Now, the committee is aware that NASA contracted with the J.H. Wiggins Co. to provide this information for you. But subsequently it became evident, as we understand it in this committee, that the procedure to assign probabilities to these various accident scenarios needed to be looked at again.

This committee has in its possession a letter that is dated March 1984 from the Department of Energy to NASA suggesting that NASA review four reports, one which included a study done by the Teledyne Corp. Was there any action or response to the letter from the Department of Energy to NASA, Dr. Silveira?

Dr. SILVEIRA. There was no letter issued back. There were recommendations made in the Teledyne report of things that we should do. As I say, when we went through the review that we conducted in mid-1984——

Mrs. LLOYD. Did you say you did not get a letter from the Department of Energy?

Dr. SILVEIRA. No, ma'am. We did not respond back to that request by letter that I know of.

Mrs. LLOYD. But you did receive a letter.

Dr. SILVERIRA. Yes, ma'am.

Mrs. LLOYD. But you did not respond back by letter.

Dr. SILVEIRA. By a letter on that specific issue We did establish a committee that Dr. Aaron Cohen at JSC chaired to look at the Teledyne report and other reports that we had at that time to look at their approach in assessing these probabilities.

Mrs. LLOYD. But you did review the applicability of the report contained in this shuttle data book.

Dr. SILVEIRA. Right. And then our answer back to DOE on what we thought the probabilities were, of course, in the shuttle data book that we forwarded to them for their use and their analysis that they perform.

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Mrs. LLOYD. Did you take into consideration this report that was done by Teledyne?

Dr. SILVEIRA. Yes, ma'am.

Mrs. LLOYD. If you disagreed with the numerical calculations—Dr. Silveira, what was the real basis for your disagreement?

Dr. SILVEIRA. Partially because again it came through a statistical analysis in going back and looking at failures that had been encountered in the past. We used the other approaches, I said, in looking at the reliability—the individual elements of the system. A lot of that data base consisted of vehicles even though we had gone back with the INSRP panel to try to remove all of the data out of that data base that we thought was not applicable. In other words, there was a lot of smaller vehicles that were not designed for the reliability that we thought were designing the SRB's on the shuttle to, so we looked at that, and again using the statistical analysis, we thought, came out with a pessimistic answer.

We used our other approach, and that is where we have a difference of opinion between the——

Mrs. LLOYD. Will you revisit the Teledyne report at the present time in view of the happenings?

Dr. SILVEIRA. Would we do what?

Mrs. LLOYD. Do you plan to review the Teledyne report?

Dr. SILVEIRA. We have gone back and done that since that time to make sure that there was nothing in there that we would change our opinion on. Now the thing that we feel is that the number that we would use for the probability failures for FSAR is indeed our design objective, and we are going to do everything possible on the redesign of the SRB before we fly again to hopefully achieve that reliability number.

Mrs. LLOYD. Thank you very much. Mr. Nelson.

Dr. SILVEIRA. Do you want me to answer your question first?

Mr. NELSON. No, let me ask it.

Good afternoon to you. All right, let's talk first about these reports. There was the Wiggins review of shuttle Centaur failure, then followed by this Teledyne, and then Sandia looked at both the Wiggins and the Teledyne reports, and in some cases said that they are both wet, and we have our own analysis.

Dr. SILVEIRA. Right.

Mr. NELSON. What is NASA's assessment of these reliability analyses as put forth in these three reports?

Dr. SILVEIRA. Well, again, Mr. Chairman, I think, as I tried to go through, is that they approach it through a statistical analysis based on past experience of vehicles. We feel that data base, in many cases, is not applicable to what we are doing. We feel that our design was done with more reliability in the system. If you would take a portion of that data base, if you like, and say that I only use very large, solid data, principally 120-inch solid data that is used on a Titan III, it would say there has never been an in-flight failure. And we think that using a number iike 10 to the minus 3, as suggested, is probably a little pessimistic from that viewpoint.

Mr. NELSON. How much is 10 to the minus 3?

Dr. SILVEIRA. Like 1 in 1,000.

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Mr. NELSON. One of the reports said 1 in 1,000. Another one said 1 in 10,000.

Dr. SILVEIRA. Right.

Mr. NELSON. Wiggins said 1 in 10,000.

Dr. SILVEIRA. Right.

Mr. NELSON. Sandia said how much?

Dr. SILVEIRA. I'm sorry, I don't remember that number right off hand. It has been some time since I have looked at that.

Mr. NELSON. They didn't come out with a specific evaluation.

Well, anyway, whatever it is, whatever the probability is, somebody's numbers, but Sandia was saying—the Sandia report here was saying that the SRB's, the solid rocket boosters, are in fact the more likely failure, and it derives the statistics and the numbers on the probabilities. Is that how you read it?

Dr. SILVEIRA. The probability as far as having a launch failure, yes, sir. When you look at the total answer at the end as far as if I do have the failure and what that means to the end result, a lot of that gets factored out. It doesn't show up with the same—an order of magnitude or two orders of magnitude difference in the answer.

Mr. NELSON. All right, you are the chief engineer. Now, what do you project the reliability factor to be for the SRB's on the space shuttle?

Dr. SILVEIRA. Of course, we feel if you look at what a 10 to the minus 3 is compared to, in our case, what we say is 10 to the minus 5, we feel that you have to get to the level where a failure is highly unlikely, which says that is a 10 to the minus 5 number. If we said we were going to live with the 10 to the minus 3, it would say that there is still a probable event that you would have a failure. We don't feel that we can fly the shuttle if we feel like it is probably that we are going to have a failure. Our design objective is not to do that.

Mr. NELSON. All right, so your answer is that you believe the reliability of the SRB's in the context of this hearing on the RTG's is 10 to the minus 3 or 10 to the minus 5?

Dr. SILVEIRA. It would be 10 to the minus 5, and that is our design objective.

Mr. NELSON. Which is 1 in 10,000.

Dr. SILVEIRA. 1 in 100,000.

Mr. NELSON. 1 in 100,000.

Dr. SILVEIRA. Yes, sir, one more zero.

Mr. NELSON. OK, 1 in 100,000. All right, now, that is the SRB's on the space shuttle which, of course, have a higher reliability than SRB's that are strapped on to other vehicles, so let's examine some of the experience of the SRB's on other vehicles.

You have got a strap on that has been on the Titan 2-C and the Titan 34-D. What has been the flight record of those Titan strap-ons?

Dr. SILVEIRA. Never have had a flight failure with those.

Mr. NELSON. Never had a flight failure on the SRB's on those two.

Dr. SILVEIRA. No, sir.

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Mr. NELSON. OK, and it is the solids, the solid rocket boosters that basically drive the statistics on this probability of explosion; is that correct?

Dr. SILVEIRA. In the numbers that are used in the analysis, used by INSRP, the highest probability is the failure of the solid, which is the 1 times 10 to the minus 3 number.

Mr. NELSON. When you say you have never had a failure on the strap-on solids on the Titan 2-C and the Titan 34-D, how many times are we talking about flying those?

Dr. SILVEIRA. I think it is in excess of 174 [1] motors that have flown.

Mr. NELSON. 200 motors.

Dr. SILVEIRA. Yes, sir.

Mr. NELSON. And how many are strapped on the Titan 2-C?

Dr. SILVEIRA. Well, there are two on each flight.

Mr. NELSON. Two on each.

Dr. SILVEIRA. Yes, sir.

Mr. NELSON. So, within 100 flights with two solid rockets each.

Dr. SILVEIRA. Right.

Mr. NELSON. And again we are talking about solid rocket motor boosters that are considered more reliable than the ones that you just cited on the Titan 2-C's and the Titan 34-D's.

Dr. SILVEIRA. Yes, sir, when we initially designed the SRB for the shuttle, because we looked at what you would have to do to provide an abort capability during the first stage, we decided that we had to design the solid to be very, very reliable. Therefore, we went and used higher design margins than you would normally in the structure on the case of the motor. We used additional margins in designing the insulation that you put into the nozzle of the motor. We also went to a propellant P-ban formulation that was not the highest solid propellant available at the time mainly because we knew more about it, and we figured it was a more stable combination on that.

We really designed to the conservative side in designing the SRB. As a result, we thought we had an SRB that was more reliable than any SRB that had been designed before.

Mr. NELSON. OK, now you know we are throwing out numbers here. One report says 1 in 1,000. Another one says 1 in 10,000, and you are saying 1 in 100,000. Now how do you come up with those numbers?

Dr. SILVEIRA. Well, again, the 1 in 1,000 number comes about from starting from a statistical base. It says: "Examine all the previous failures in how many vehicles you have flown." Again, the statistical method will get you to about 1 in 100 as a result of that. The people who were running those numbers said: "We think it is more reliable than that. We think if we use 1 in 1,000 that that would be our best judgment than what we thought it was."

We come from the other direction in looking at the system with the redundancy that we thought we had in seals and also in the extra margins that we had in the structure in the thermal protection. We put additional insulation into the case to prevent burn-

[1] Flight motors plus 20 static firings for a total of 174 motors successfully fired.

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throughs through the case and the like. We said we think we have an improbable failure in the SRB, and it should be more 10 to the minus 5.

Mr. NELSON. Is that the normal kind of deduction as you come up with various statistical probabilities? Do you normally do that?

Dr. SILVEIRA. We do not ourselves use the statistical probabilities. We had to derive these for the DOE analysis, and we came to those probabilities based on engineering judgment in review of the design rather than taking a statistical data base, because we didn't feel we had that.

Mr. NELSON. Well, why? Why do you use engineering judgment instead of the numerical or the statistical probabilities?

Dr. SILVEIRA. Because we think that the statistical probabilities give you a very, very pessimistic answer. We attempted in the Apollo Program to do an analysis along that line, to look at user statistics that develop the probability of vehicle working, or a mission to the Moon working, and it was so pessimistic that we did away with that study.

Mr. NELSON. How much testing would you have to have to demonstrate that an SRB had numerical reliability of say, 1 in 1,000?

Dr. SILVEIRA. Well, if you use just the pure statistics—if you had no failures in 1,000 firings, you would still remain with 3 failures possible in the next 1,000 events. So it would be in excess of—I'm purely guessing, but much, much more than 1,000 firings would have to be conducted.

Mr. NELSON. In other words, if you were going to demonstrate that you only had a failure of 1 in 1,000, you would have to fire it 1,000 times.

Dr. SILVEIRA. Yes, sir. Recognizing that even a static firing on the ground doesn't totally duplicate the flight environment, there is still an unknown, even after you do that as to whether you really have demonstrated the flight vehicle.

Mr. NELSON. Can you draw for me a comparison of why or why it is not wise to use the FAA aircraft certification methodology on shuttle reliability?

Dr. SILVEIRA. I'm not sure I can really do that for you, Mr. Chairman. I think in many cases, as compared to what I have seen and what they go through in certifying an aircraft, I think that our test program and our qualification programs are much greater than what is used on aircraft.

Mr. NELSON. Of course, what you do, you have a different kind of system. You can't go out and fly a shuttle like you can an aircraft every day. And the cost, the expense, the time, et cetera, of trying to fire something 1,000 times—you know, I mean that is a given, but for the record we may as well say that—but this is interesting because everybody is bandying about these statistics on the basis of engineering judgment and so forth. So I am trying to understand some of that.

Let's get back to my initial question. The question is, testimony has already said that the blast overpressure was somewhere in the range of 200 to 400 pounds per square inch in the tragic explosion of *Challenger*. Do you agree with that figure?

Dr. SILVEIRA. Again, what we are attempting to do at the present time is go back and analyze that data. I think that is a very pre-

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liminary number at the present time. We still have to use the resources we have to try to make an estimate of what that yield was and then back that number out. I would feel that it is probably in that range.

Mr. NELSON. Do you agree that the RTG is designed at 2,200 pounds per square inch?

Dr. SILVEIRA. Yes, sir.

Mr. NELSON. All right, what would have been the pounds per square inch had *Challenger* been fitted out for Ulysses or Galileo?

Dr. SILVEIRA. Well, the question I am prepared to answer is the one you asked if this even had occurred on the pad.

Mr. NELSON. Yes, but I haven't gotten there yet.

Dr. SILVEIRA. OK. What we really do as far as yields is give a curve that has pressure against probability. That is in this shuttle data book that we gave to DOE. You go back to those curves and try to make an estimate against a probability number to come out with yields. Now, in the case of a flight vehicle in flight where you had everything worse on worse, you may be as high as 2,000 pounds per square inch, if you had total mixing before you had ignition of the Centaur.

Mr. NELSON. So at the height and speed that *Challenger* blew 74 seconds approximately, fraction of a second underneath 74, you are saying that the pounds per square inch with the ignition of a Centaur on board would be in the range of 2,000 pounds per square inch.

Dr. SILVEIRA. Worse case.

Mr. NELSON. Worse case. Therefore, it would survive. The RTG would survive in tact.

Dr. SILVEIRA. Of course, as indicated before, the overpressure is one of the failure scenarios. You still have the probability of fragmentation that would actually damage the structure of the RTG. That is a tougher model to go after in trying to get that kind of deal.

Mr. NELSON. I understand.

Dr. SILVEIRA. Specifically, what we are looking at *Challenger* for is to understand how the vehicle broke up and see if we can get a better understanding of what fragmentation it was.

Mr. NELSON. Well, when you finish that analysis, of course we would love to have you back down, so you can share that with us.

Now, let's go back to the pad, now. OK, worse case scenario.

Dr. SILVEIRA. Worse case on the pad, again——

Mr. NELSON. With a Centaur.

Dr. SILVEIRA. With a Centaur, would consider, the worst yield you would get out of a Centaur. Again, in this case it would be in the order of about 2,000 pounds per square inch as far as the overpressure is concerned.

Mr. NELSON. Overpressure. Now, how about the collision with the steel on the launch tower?

Dr. SILVEIRA. Well, the analysis that has been done at the present time and assuming collision, again, comes from the conservative side. The service structure is considered to be a total flat plate—in other words, it has a larger area than really exists there in a like. I think Mr. Lombardo has said, and we don't disagree with the analysis he has, is that, yes, there is a possibility in being

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able to rupture the RTG and actually have a clad that would be stripped and you would have a release on the pad.

Mr. NELSON. Is there anything that you think—and I thank you for your testimony. You have clarified a lot of things in my mind. If it seems like I am asking you tough questions, I intend to, and I will continue to.

Dr. SILVEIRA. All right, sir.

Mr. NELSON. Is there anything that you think could be done to make the shuttle configured with the Centaur vis-a-vis the RTG's on board safer?

Dr. SILVEIRA. I think we had looked at that previously. I think, as you know, we looked at putting shielding around the RTG's to increase the probability of them being able to survive, particularly the fragmentation. We found that not to be a terribly large increase in being able to cut down the probability of that happening.

Again, at this time, as we are doing with the entire vehicle, we will go back and see if there are any new ideas or if someone has an idea that they can come forward with that would basically enhance that capability, and, of course, if we can, we will go do that.

Mr. NELSON. When do you think that you are going to have the data from your analysis as to the fragments and so forth from the *Challenger* explosion?

Dr. SILVEIRA. Well, like usual we will probably have several groups do that and get several answers, and it will be a matter of sitting down with those and trying to take what we think to be the best model and the best answer from that. I would say we are probably 3 or 4 months away from having a total answer on that.

Mr. NELSON. Why don't we see if we can visit and have some preliminary stuff come in about June.

Dr. SILVEIRA. OK. Yes, sir.

Mr. NELSON. Madam Chairman, since we are specifically on the question of the RTG's, I am limiting my questioning, my probing, as to how that lines up with the RTG's.

Mrs. LLOYD. That is the scope of the hearing, but evidently the recent events certainly do play on our hearing today, and that is one of the main reasons we are here, so I don't think that is out of line.

Mr. NELSON. Well, what I am saying is that there is another whole scope of questioning that is opening up here that I will just save for a later day that we will get into on our committee, regarding the question of the shuttle Centaur interface, but I will stop my questioning there with regard to the RTG.

Mrs. LLOYD. Thank you very much, Mr. Nelson.

Mr. Fawell.

Mr. FAWELL. I have no questions.

Mrs. LLOYD. Thank you very much, Dr. Silveira, for appearing before this subcommittee today and we will be submitting questions in writing for you to answer.

Mr. Keller, we certainly look forward to your testimony at this time, and you may proceed.

Mr. KELLER. Madam Chairman, with your permission, I will submit the entire testimony for the record and summarize.

Mrs. LLOYD. Very well.

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Mr. KELLER. Madam Chairman, Mr. Chairman, and members of the subcommittee, thank you for the opportunity to testify before the Subcommittee on Energy Research and Production and the Subcommittee on Space Science and Applications on the use of radioisotope thermoelectric generator power sources for spacecraft.

I am here today to comment on the specific necessity of the payload offices within NASA to rely on RTG's for the execution for certain of our programs. Since the advent of space probes, there has been a continuous search for more effective and more efficient power sources. In light of the limitations and the weight penalties associated with batteries alone, solar cells combined with batteries became the workhorses of the early U.S. space probes. However, as we reached out further from the Sun to explore the cosmos, the restrictions of those systems became apparent. At these greater distances, we became limited in our capability to extract the Sun's energy with practically sized solar arrays and consequently have explored the use of nuclear power for some of our more ambitious space programs.

RTG's have been used for both Earth orbital and planetary missions where solar conversion power sources are impractical, although they are no longer considered for low Earth orbit. RTG's are used on unmanned spacecraft destined to travel beyond the planet Mars, where the faintness of the Sun's radiation precludes the use of solar panels. RTG's also maintain their power for a longer period of time than their equivalent solar powered systems—making them ideal power supplies for long planetary missions. The radioisotope fuel is used as a source of heat to produce electrical energy, and no nuclear fusion or fission processes are required.

If solar cells were used to provide power for outer planet missions like Voyager or Galileo, they would require massive solar arrays. The energy from the Sun decreases the square of the distance from the Sun. Since Jupiter is more than five times the distance from the Sun that the Earth is, the energy from the Sun at Jupiter is only one twenty-fifth that at Earth. At the distance of Saturn, that ratio reduces to one one-hundredths at Uranus to one four-hundredth, and at Neptune to one nine-hundredth. A typical spacecraft, like Galileo, requires approximately 500 watts of power. Near the Earth, this requirement can be satisfied with 50 square feet of solar array. At Jupiter, this solar array would have to increase in size to 1,250 square feet. At Saturn, the size would grow to 5,000 square feet. At Neptune, a similar power requirement would necessitate a solar array of almost 50,000 square feet. This is the size of an entire football field.

Since 1961, the United States has launched 22 NASA and military spacecraft using RTG power sources. Table 1 of my statement illustrates the history and status of these missions. Three of those missions were aborted, all without serious environmental impact.

Referring to table 1, the five RTG's left on the Moon during the Apolio Program powered instruments which provided invaluable scientific data. In light of the long lunar nights, these data could not have been provided by any other power source. The Viking mission, with its two orbiters and two landers, left four RTG's on the surface of Mars. Again, in light of the reduced solar energy avail-

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able at Mars, no other practical power source, at an affordable weight, could have been used.

In summary, there is no alternative to radioisotope power sources if we are to continue exploration of the solar system. The mind-boggling imagery recently received from Uranus, and earlier from Saturn and Jupiter, would have been impossible without RTG's. We would never have known about the volcanic activity on Io, details of the Saturn rings, the strange and varied worlds of the outer planet moons, or Uranus' strange magnetic field were it not for RTG's.

A Mars lander loaded with scientific instruments and pictures of the Martian surface would never have been possible. The Apollo lunar surface experiments could never have remained operable and given us their seismic observations through the long lunar night without RTG power supplies. Until some as yet unknown source of electrical power is discovered, the world's planetary exploration programs are dependent on the use of RTG power sources. NASA has used these devices for 25 years, and I believe has done so in a safe and responsible manner. These programs have resulted in an increase in man's understanding of the solar system in which we live which was beyond even the dreams of the explorers who came before us.

Mr. Chairman, I would be pleased to respond to any questions.

[The prepared statement of Mr. Keller follows:]

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Statement of

Mr. Samuel W. Keller
Deputy Associate Administrator

Office of Space Science and Applications

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (NASA)

before the

Subcommittee on Energy Research and Production
and the
Subcommittee on Space Science and Applications
Committee on Science and Technology
U.S. House of Representatives

Madam Chairman, Mr. Chairman, and Members of the Subcommittees:

Thank you for the opportunity to testify before the Subcommittee on Energy Research and Production on the Use of Radioisotope Thermoelectric Generator (RTG) Power Sources for Spacecraft.

Since the advent of space probes, there has been a continuous search for more effective and more efficient power sources. In light of the limitations and the weight penalties associated with batteries alone, solar cells combined with batteries became the workhorses of the early U.S. space probes. However, as we reached out further from the sun to explore the cosmos, the restrictions of those systems became apparent. At these greater distances, we became limited in our capability to extract the sun's energy with practically-sized solar arrays and, consequently, have explored the use of nuclear power for some of our more ambitious space missions

RTG's have been used for both Earth orbital and planetary missions where solar conversion power sources are impractical, although they are no longer considered for low earth orbit. RTG's are used on unmanned spacecraft destined to travel beyond the planet Mars, where the faintness of the sun's radiation precludes the use of solar panels. RTG's also maintain their power for a longer period of time than their equivalent solar powered systems--making them ideal power supplies for long planetary missions. The radioisotope fuel is used as a source of heat to produce electrical energy, and no nuclear fusion or fission processes are required.

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The heat from the decay of the radioactive material generates an electric current in a device called a unicouple. This is essentially a thermocouple, or a device made of dissimilar metals, and generates electric current as a result of an applied temperature difference. The radioisotope provides the high temperature, and the cold vacuum of space provides the cold temperature.

If solar cells were used to provide power for outer planet missions like Voyager or Galileo, they would require massive solar arrays. The energy from the sun decreases as the square of the distance from the sun. Since Jupiter is more than five times the distance from the sun that the Earth is, the energy from the sun at Jupiter is only 1/25 that at Earth. At the distance of Saturn, that ratio reduces to 1/100, at Uranus to 1/400, and at Neptune to 1/900. A typical spacecraft, like Galileo, requires approximately 500 watts of power. Near the Earth, this requirement can be satisfied with 50 square feet of solar array. At Jupiter, this solar array would have to increase in size to 1,250 square feet. At Saturn, the size would grow to 5,000 square feet. At Neptune, a similar power requirement would necessitate a solar array of almost 50,000 square feet; this is the size of an entire football field.

Not only is it difficult to package such large solar arrays, but they would add prohibitive weight to the spacecraft. The required Galileo solar array of 1250 square feet would weigh over 1000 lb., while the comparable RTG power source is only a small fraction of that weight. The array required by Voyager at Neptune would weigh about 25 times what the entire spacecraft weighs now. In addition, the configurational complexities associated with large solar arrays would obstruct the visibility of the scientific instruments and thereby severely impede their information return. It is clear that the incomparable science the world has derived from planetary missions through the years, as exemplified by the recent Uranus encounter, could not have been achieved without RTG power sources. The same amount of solar energy that could power a 100 watt bulb at Earth would not even power a flashlight at Saturn. The outer planets simply could not have been explored without the use of radioisotope power sources.

Since 1961, the U.S. has launched 22 NASA and military spacecraft using RTG power sources. Table 1 shows the history and status of those missions. Three of those missionss were aborted, all without serious environmental impact: In 1968, the Nimbus-B RTG was recovered intact after a launch failure; in 1970, the Apollo 13 RTG was jettisoned in 10,000-20,000 ft. of water in the Pacific; and in 1964, the Transit-5BN-3 RTG burned up during reentry in accordance with the design philosophy of RTG's at that time. Table 2 gives the characteristics of the remaining earth orbiting satellites and their expected orbital lifetimes.

Referring to Table 1, the five RTG's left on the moon during the Apollo program powered instruments which provided invaluable scientific data. In light of the long lunar nights, these data could not have been provided by any other power source. The Viking mission, with its two orbiters and two landers, left four RTG's on the surface of Mars. Again, in light of the reduced solar energy available at Mars, no other practical power source, at an affordable weight, could have been used.

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In addition to the issue of available energy at the outer planets discussed above, the issue of weight for planetary spacecraft has special significance. Since planetary spacecraft require an injection stage (and frequently a retropropulsion stage for planetary orbits), the issue of weight minimization is of paramount importance. Each pound of added payload weight will usually add five or more pounds of required launch vehicle propulsion. Weight increases for planetary spacecraft of this magnitude will frequently force a more expensive mission or put it beyond the realm of possibility.

In summary, there is no alternative to radioisotope power sources if we are to continue exploration of the solar system. The mindboggling imagery recently received from Uranus, and earlier from Saturn and Jupiter, would have been impossible without RTG's. We would never have known about the volcanic activity on Io, details of the Saturn rings, the strange and varied worlds of the outer planet moons, or Uranus' strange magnetic field were it not for RTG's. A Mars lander loaded with scientific instruments and pictures of the Martian surface would never have been possible. The Apollo lunar surface experiments could never have remained operable and given us their seismic observations through the long lunar night without RTG power supplies. Until some as yet unknown source of electrical power is discovered, the world's planetary exploration programs are dependent on the use of RTG power sources. NASA has used these devices for twenty-five years, and I believe has done so in a safe and responsible manner. These programs have resulted in an increase in man's understanding of the solar system in which we live which was beyond even the dreams of the explorers who came before us.

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Table 1 - U.S. History of RTG Power Source Use

Power source[1]	Spacecraft	Mission type	Launch date	Status
SNAP-3A	TRANSIT 4A	Navigational	June 29, 1961	Successfully achieved orbit
SNAP-3A	TRANSIT 4B	Navigational	Nov. 15, 1961	Successfully achieved orbit
SNAP-9A	TRANSIT-5BN-1	Navigational	Sept. 28, 1963	Successfully achieved orbit
SNAP-9A	TRANSIT-5BN-2	Navigational	Dec. 5, 1963	Successfully achieved orbit
SNAP-9A	TRANSIT-5BN-3	Navigational	April 21, 1964	Mission aborted burned up on reentry
SNAP-19B2	NIMBUS-B-1	Meteorological	May 18, 1968	Mission aborted;heat source retrieved
SNAP-19B3	NIMBUS III	Meteorological	April 14, 1969	Successfully achieved orbit
SNAP-27	APOLLO 12	Lunar	Nov. 14, 1969	Successfully placed on lunar surface
SNAP-27	APOLLO 13	Lunar	April 11, 1970	Mission aborted on way to moon.Heat source returned to south Pacific Ocean.
SNAP-27	APOLLO 14	Lunar	Jan. 31, 1971	Successfully placed on lunar surface
SNAP-27	APOLLO 15	Lunar	July 26, 1971	Successfully placed on lunar surface
SNAP-19	PIONEER 10	Planetary	Mar. 2, 1972	Successfully operated to Jupiter and beyond
SNAP-27	APOLLO 16	Lunar	April 16, 1972	Successfully placed on lunar surface
TRANSIT-RTG	"TRANSIT" (TRIAD-01-1X)	Navigational	Sept. 2, 1972	Successfully achieved orbit
SNAP-27	APOLLO 17	Lunar	Dec. 7, 1972	Successfully placed on lunar surface
SNAP-19	PIONEER 11	Planetary	April 5, 1973	Successfully operated to Jupiter and Saturn and beyond
SNAP-19	VIKING 1	Mars	Aug. 20, 1975	Successfully landed on Mars
SNAP-19	VIKING 2	Mars	Sept. 9, 1975	Successfully landed on Mars
MHW	LES 8	Communications	Mar. 14, 1976	Successfully achieved orbit
MHW	LES 9	Communications	Mar. 14, 1977	Successfully achieved orbit
MHW	VOYAGER 2	Planetary	Aug. 20. 1977	Successfully operated to Jupiter and Saturn and beyond
MHW	VOYAGER 1	Planetary	Sept. 5, 1977	Successfully operated to Jupiter and Saturn and beyond

[1]SNAP stands for Systems for Nuclear Auxiliary Power. MHW stands for the Multi hundred Watt RTG.

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Table 2 - Characteristics of Earth-Orbiting U.S. Satellites Containing RTGs

Spacecraft	Launch Date	Period, min	Inc., deg	Apogee, km	Perigee, km	Power Source	Inventory of Pu-238 at Launch curies	Expected Orbital Lifetime, years	Disposal Mode
Transit 4B	6/29/61	103.7	66.8	993	881	SNAP-3	1,800	570	Burnup
Transit 4B	11/15/61	105.7	32.4	1103	953	SNAP-3	1,800	1200	Burnup
Transit 5BN1	9/28/63	107.3	89.8	1135	1072	SNAP-9A	17,000	1900	Burnup
Transit 5BN2	12/5/83	107.0	89.9	1119	1067	SNAP-9A	17,000	1800	Burnup
Nimbus III	4/14/69	107.3	99.7	1135	1074	SNAP-19	37,000	3600	Intact Reentry
"Transit" (TRIAD 01-0X)	9/2/72	100.6	90.1	838	742	RTG	24,000	150	Intact Reentry
LES 8/9	3/15/76	one sidereal day	25.0	coplanat geosynchronous orbit		MHW	280,000 (4 MHWs)	>10000	Intact Reentry

Note: The "Disposal Mode" column indicates the manner in which each RTG was designed to respond to atmospheric reentry. Before 1967, RTGs were designed to burn up at high altitude to enhance the dispersal of the plutonium, (as did the SNAP-9A which was abortively launched in 1964. Since 1967, RTG systems have been designed to survive reentry intact to allow their recovery on Earth and the return of their plutonium inventories to positive control.

Mr. NELSON. Thank you very much, Mr. Keller, and indeed NASA has had an extraordinary record, as you have pointed out here. That is not the question of this hearing. All the way starting from 1961 in which there have been RTG power sources all the way through late 1977 in which you pointed out very well that going to such far reaches of the solar system in Pioneer X and XI, Viking I and II on Mars, Voyager I and II, Voyager bringing those tremendous new data back from Jupiter and Saturn, Uranus and Neptune. As a matter of fact, if you go right down here into our Space Subcommittee room, you will see the picture of the surface of Mars that came back from Viking, and that is just extraordinary, and so indeed I think it is important to underscore that point that but for these energy sources we would not have been able to achieve this expansion of man's knowledge and space science that we have.

The question here is that we want to look at in the course of this hearing is now that we have had this tragic cataclysmic explosion that no one planned on, even though you understand risk and you accept that there is a certain amount of risk when you fly on an extremely complicated system flying into a very hostile environment, nevertheless when you add to that payload an RTG, naturally the questions arise, well, what is its safety, and that's what we want to get out here. And I appreciate your comments, Mr. Keller, for bringing out the fact that you had a host of, let's see, how many of these missions?

Mr. KELLER. There have actually been 22, sir.

Mr. NELSON. Twenty-three?

Mr. KELLER. Twenty-two, United States, NASA and DOE. I think there is a total of 34 RTG's on those missions.

Mr. NELSON. Thirty-four American RTG's.

Mr. KELLER. RTG's on 22 different missions.

Mr. NELSON. Thirty-four RTG's on twenty-two American missions.

Mr. KELLER. Yes, sir, for example the Voyager carried two RTG's. Galileo had two. Ulysses would have only had one.

Mr. NELSON. Do you have any idea how many Soviet nuclear energy sources there are?

Mr. KELLER. No, sir, I do not.

Mr. NELSON. Thank you, Madam Chairman.

Mrs LLOYD. Thank you very much, Mr. Nelson.

Looking back on the tragedy of January, Mr. Keller, what do you really assess as the impact of this tragedy on the Galileo and Ulysses missions.

Mr. KELLER. Madam, there is, of course, the obvious immediate impact of a launch slip.

Mrs. LLOYD. Well, of course, the launches were scheduled for May. Rather than moving the date back, what is the further impact on the missions?

Mr. KELLER. I think the impact other than the change in the launch date is that we, as Dr. Silveira pointed out, and as the representative from DOE pointed out, are collectively going to reassess the risk involved in these kinds of missions. As I tried to point out in my testimony, we have no alternative if we intend to explore the outer planets to the use of RTG power sources.

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It is clearly, though, incumbent on us to do everything that we can do to ensure that we understand the risk and to convince this committee and the American public that we have done everything that is possible to minimize that risk, and we are working in that direction now.

Mrs. LLOYD. Well, I think what really disturbs me, Mr. Keller, is that this is still a rather open issue that indeed we are looking at collective engineering judgment by NASA on the events that occur, whereas then we are looking at the issue in terms of numbers, and we are looking at an entirely different picture, and obviously you are making your assessment entirely on your engineering judgments.

If it is my understanding, then, that there is no other power options available for the Galileo and Ulysses missions; is that correct?

Mr. KELLER. Yes, ma'am, that is correct.

Mrs. LLOYD. It is the only source of power that is small enough and predictable enough and that really can perform the mission as intended.

Mr. KELLER. Yes, ma'am.

Mrs. LLOYD. Well, since you don't have another power option, do you feel that this is going to require additional tests on our RTG's?

Mr. KELLER. I would be reluctant to speculate on additional RTG tests, because that is certainly one area that I am not an expert in. Certainly from the point of view of the payload office, which I represent, the people who build the satellites, and who design the missions, we intend to cooperate with those parts of both our agencies and DOD who will determine in a better manner than I can exactly what is necessary to convince ourselves and the committees and the various people who oversee us that the risk in these missions has been minimized to the point where it is an acceptable risk, and we have been committed to that throughout this process, and I think the *Challenger* tragedy will cause a reassessment, another look at the standards we have established, and I think there will be additional tests, although I am not in the position to identify right now what they would be.

Mrs. LLOYD. Well, truly, our space program is a source of national pride that all Americans—just about all Americans identify with. So it was not only a tragedy for our Nation, but it was a personal tragedy for Americans, and we do want to make the assessments that are logical to go on with our programs. Certainly it is the intent of this committee to continue to work with the Department of Energy and NASA to really not only go from here, but to certainly improve on our capabilities as well.

Mr. Nelson.

Mr. NELSON. Thank you, Madam Chairman. Let me explore with Dr. Silveira another thought. We have talked about the safety aspect with regard to the RTG's when you add the Centaur upper stage into the cargo bay, and, Dr. Silveira, you talked about that brings the potential explosiveness back in there into the cargo bay only 15 feet from the RTG.

You also testified, however, that your overpressure worse case scenario is 2,000 pounds per square inch, whereas you are designed for 2,200 pounds per square inch. All right, now here is my question: take a launch vehicle of an ELV. I have already explored with

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you the question of the greater reliability of shuttle and its SRB's, solid rocket boosters, versus the ELV's, expendable launch vehicles, such as Titan, Titan 34-D or the CELV, so we do assume that we have greater reliability in your man-rated system, but the difference is on top of the ELV is where you have your RTG instead of down close to the explosive potential.

OK, so in one you have got a man-rated system that is safer, but in another ELV side, it is less safe than the man-rated system, but the payload is up further away from the potential fireball. You want to give me your professional opinion as to the two different styles of launch capability vis-a-vis the RTG?

Dr. SILVEIRA. Everything you have said is indeed true, and there you are taking the risk of having an event in the first place, as compared to, say, flying on an ELV that doesn't have the same reliability of, say, delivering that payload to orbit, and risking the reentry of that unit, and the course will rupture, and you know any accident scenario that will be associated by not accomplishing a successful mission there.

What we hopefully try to achieve all the time is making it a successful mission, and that's where we think that is the best place to put your money, and the best place to be flying your vehicles rather than taking an increased risk in not achieving the objectives of that particular mission, and then having to design and go through the survival mode of a failure on an ELV.

Mr. NELSON. So you are saying it is safer on the shuttle.

Dr. SILVEIRA. I really hope so, yes, sir. Depending on what we learn from this accident, we may consider modifications to some of the probabilities for the RTG mission, even looking at if there are any design improvements that can be made to the system. However, I still believe that a combination of the analytical techniques we use for minimizing the risk is still superior to any numerical analysis approach.

Mr. NELSON. Thank you, Madam Chairman.

Mrs. LLOYD. Thank you, Mr. Nelson.

Dr. Silveira, thank you, and Mr. Keller, thank you also.

I'm sorry, Mr. Fawell?

Mr. FAWELL. I have no questions.

Mrs. LLOYD. Our next witnesses compose the Interagency Nuclear Safety Review Panel [INSRP]. We will hear from Mr. Leven Gray from NASA. He will be accompanied, however, by Col. J. Joyce, the Department of Defense; and by Mr. Norman Klug from the Department of Energy.

Welcome, gentlemen, to our hearings today. Mr. Gray, we look forward to your testimony.

STATEMENTS OF LEVEN GRAY, INSRP NASA COORDINATOR, ACCOMPANIED BY COL. JOHN JOYCE, INSRP DOD COORDINATOR; AND NORMAN KLUG, INSRP DOE COORDINATOR

Mr. GRAY. Thank you, Madam Chairperson. I would like to introduce my colleagues, Mr. Norman Klug, on my left, is the Department of Energy INSRP Coordinator and Col. John Joyce on my right, who is the DOD Coordinator.

Mrs. LLOYD. Welcome to the hearings.

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I believe, Mr. Gray, if you would move the speakers closer to you, we could hear better and those in the audience as well.

Mr. GRAY. Thank you, Madam Chairwoman, if it pleases you, I have a statement that is about 9 minutes, and I would like to just read it into the record.

Mrs. LLOYD. Without objection your complete statement will be a part of the record, and you may summarize as you wish.

Mr. GRAY. Thank you, Madam Chairwoman, Mr. Chairman, and distinguished members of the subcommittees, we are pleased to have this opportunity to discuss the role of the Interagency Nuclear Safety Review Panel, which is referred to as INSRP, in evaluating the nuclear risks associated with launching space vehicles with nuclear systems on board.

In our testimony, we will discuss the makeup of the INSRP, the manner in which it functions as a part of the aerospace nuclear safety review process, and the status of our reviews of the Galileo and Ulysses missions. In accordance with your request, this testimony will primarily address the INSRP process and procedures.

Presidential Directive NSC-25 establishes the basic procedure to be followed for launching space nuclear systems. An environmental impact statement or a nuclear safety evaluation report is prepared, and in addition, Presidential approval is required for launches of spacecraft utilizing radioactive sources containing a significant quantity of radioactive material.

According to the directive, an ad hoc Interagency Nuclear Safety Review Panel consisting of members from the Department of Defense, Department of Energy, and NASA evaluates the risks associated with the mission and prepares a Nuclear Safety Evaluation Report. The Nuclear Regulatory Commission is requested to participate as an observer when appropriate. The Environmental Protection Agency also is invited as an observer. The head of the sponsoring agency requests the President's approval for the flight through the Office of Space Science and Technology Policy. The Director of OSTP is authorized to render approval for such launchings unless he considers it advisable to forward the matter to the President for decision.

Madam Chairman, a copy of the Presidential directive will be provided to the subcommittee for the record.

Mrs. LLOYD. And it will be made a part of the record as well.

[The information follows:]

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THE WHITE HOUSE

WASHINGTON

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December 14, 1977

PRESIDENTIAL DIRECTIVE/NSC-25

TO: The Secretary of State
The Secretary of Defense
The Secretary of Energy
The Secretary of the Interior
The Secretary of Agriculture
The Secretary of Commerce
The Secretary of Health, Education, and Welfare
The Secretary of Transportation
The Acting Director, Office of Management and Budget
The Assistant to the President for National Security Affairs
The Chairman, Council on Environmental Quality
The Director, Office of Science and Technology Policy
The Director, Arms Control and Disarmament Agency
The Administrator, Environmental Protection Agency
The Administrator, National Aeronautics and Space Administration
The Director, National Science Foundation
The Chairman, Nuclear Regulatory Commission

SUBJECT: Scientific or Technological Experiments with Possible Large-Scale Adverse Environmental Effects and Launch of Nuclear Systems into Space

Two earlier Presidential memoranda dealt with the conduct of scientific or technological experiments that might have large-scale or protracted effects on the physical or biological environment (NSAM 235 of April 17, 1963) and the launching into space of systems involving nuclear power (NSAM 50 (revised) of April 10, 1965). These two NSAMs are hereby rescinded. The general purpose, however, behind these two directives--to give the President the opportunity to consider all factors before any such experiment is carried out--remains valid. The President has approved the policy and procedures below to accomplish that purpose.

It should be understood that experiments which by their nature could reasonably be expected to result in domestic or foreign allegations that they might have major and protracted effects on the physical or biological environment,

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CLASSIFICATION CANCELLED
BY AUTHORITY OF NSC memo, 2/25/77 to NSC 9/07/01
BY [illegible] DATE 10/25/01

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or other areas of public or private interest, are to be included under this policy even though the sponsoring agency feels confident that such allegations would in fact prove to be unfounded.

Where such experiments constitute major action either licensed or funded by Federal Agencies that significantly affect the quality of the human environment, an environmental impact statement will be prepared. The data from such statement may be used in complying with the following procedures which do not affect the requirement to comply with the provisions of the National Environmental Policy Act:

1. The head of any agency that proposes to undertake a large-scale scientific or technological experiment that might have major and protracted effects on the physical or biological environment, or on other areas of public or private interest, will call such proposals to the attention of the Director of the Office of Science and Technology Policy (hereafter the Director). The Director will consult with the Chairman of the Council on Environmental Quality (hereafter, the Chairman). Notification of such experiments will be given sufficiently in advance that they may be modified, postponed, or cancelled, if such action is judged necessary in the national interest.

2. In support of proposals for such experiments, the sponsoring agency will prepare for the Director a detailed evaluation of the importance of the particular experiment and the possible direct or indirect environmental effects that might be associated with it. The data from an environmental impact statement may be used in complying with this procedure.

3. The Director in consultation with the Chairman will review the proposals and supporting materials presented by the sponsoring agency in order to assure that the need for the experiment has been properly weighed against possible adverse effects.

4. On the basis of this review, the Director in consultation with the Chairman will recommend to the President what action should be taken on the proposed experiment. If the Director, in consultation with the Chairman, judges that adequate information is available on which to make a judgment, the Director may request that additional studies be undertaken by the sponsoring agency or may undertake an independent study of the problem. Agencies will be notified if an extended delay is anticipated in approval.

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5. In the case of experiments that have major national security implications, the head of the sponsoring agency will notify me so that I may determine on an individual basis the procedure to be followed in reviewing these experiments.

6. While the final decision to conduct such experiments must continue to reside with the government, the National Academy of Sciences and, where appropriate, international scientific bodies or intergovernmental organizations may be consulted in the case of those experiments that might have adverse effects beyond the US. When experiments are expected to have such impacts in foreign countries the Secretary of State will be notified. In arriving at decisions on specific projects, foreign policy considerations should be taken into account. Recommendation on the advisability of the courses of action will be made by the Director in consultation with the Chairman and with the sponsoring agency and the State Department as appropriat

7. Any large scale scientific or technological experiment that may involve particularly serious or protracted adverse effects will not be conducted without the President's approval. Any experiment that may involve serious or protracted adverse effects will not be conducted without the approval of the head of the department or agency involved, with, in appropriate cases, the advice of other concerned agencies.

8. To the extent that it is consistent with national security, and subsequent to approval of the experiment, there should be early and widespread dissemination of public information explaining the purpose, benefits, and assessments of impacts

9. A separate procedure will be followed for launching space nuclear systems. An environmental impact statement or a nuclear safety evaluation report, as appropriate, will be prepared. In addition, the President's approval is required for launches of spacecraft utilizing radioactive sources containing more than 20 curies of material in Radiotoxicity Groups I and II and for more than 200 curies of material in Radiotoxicit Groups III and IV (as given in Table I of the NASC report of June 16, 1970 on "Nuclear Safety Review and Approval Procedures." An ad hoc Interagency Nuclear Safety Review Panel consisting of members from the Department of Defense, Department of Energy, and National Aeronautics and Space Administration will evaluate the risks associated with the mission and prepare a Nuclear Safety Evaluation Report. The Nuclear Regulatory Commission should be requested to participate as an observer when appropriate The head of the sponsoring agency will request the President's approval for the flight through the Office of Science and

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Technology Policy. The Director is authorized to render approval for such launchings, unless he considers it advisable to forward the matter to the President for decision.

Zbigniew Brzezinski

[redacted] - GDS

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Mr. GRAY. The INSRP, established in accordance with this directive, provides an independent evaluation of the risks associated with the launch of a nuclear power system in space. The panel members are independent of the program and the panel is organized such that no single agency is dominant. The panel is an ad hoc organization which is established when a mission utilizing a nuclear power system is being planned. The current panel was established for nuclear payloads, including Galileo and Ulysses, using the space transportation system. The three coordinators in the current panel are listed in attachment 1 which is attached to our statement, along with their organizational affiliations.

The Panel is supported by subpanels sponsored by the three agencies. Subpanels are currently organized in the areas of launch abort, reentry, meteorology, oceanography, and biomedical and environmental effects. The subpanels are staffed by technical experts in these various disciplines. The current membership of the INSRP subpanels is included in attachments 2 through 7 in our statement, and their affiliations are also stated.

The independent safety review process conducted by the panel has been in place since the midsixties. The process has been used for review of diverse missions where spacecraft deployed have included Earth orbit, lunar surface, Jupiter fly-by and deep space, Mars lander, and Jupiter/Saturn fly-bys.

The aerospace nuclear safety review process is depicted in attachment 8. The program's evaluation of the safety aspects of a nuclear power system as associated with a specific space mission is provided via a safety analysis report [SAR]. These reports are the responsibility of the Department of Energy and are prepared by the Department of Energy nuclear system contractor. They contain and utilize significant input information which originates from the agencies responsible for the spacecraft, launch vehicle, the launch operations, and the launch range.

Briefly, an SAR includes a description of the mission and flight system including the appropriate details of the nuclear power system, the spacecraft, launch vehicle and the flight profile and characteristics. The SAR then develops the potential accident environments and response of the nuclear power systems to these environments. The SAR then proceeds to describe the resulting potential radiological risks. There is usually a preliminary safety analysis report, referred to as a PSAR, which is noted on your attachment 8, the updated safety analysis report, which is referred to as a USAR, and then the final safety analysis report, referred to as the FSAR.

The panel meets with the program elements to review the nuclear safety aspects of a proposed mission after the issuance of a PSAR and USAR, and frequently the FSAR. The panel and/or the subpanels meet with the program elements on an ad hoc basis during the course of the program, as determined by the status of the program activity and the nature of the safety issues at hand. Continuing interaction between the panel and the subpanels with the program assures that the panel and subpanel personnel are informed of the program events important to nuclear safety while the program is in progress.

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When INSRP personnel recognize potential problems, data, or information deficiencies or any other item which may lead to problems during a review, this information is provided to project personnel for their consideration and action. Participation during the early phases of a project does not, however, commit reviewing personnel to any particular position. An attempt is made to prevent inconsistencies, but if information comes to light at a later date, which changes the outlook on a particular problem, the reviewers operate with the latest available data.

After the review of the FSAR and any other germane documents such as test reports, additional analyses provided by the program, the panel prepares an SER. This report summarizes the panel's risk evaluation. It is important to emphasis that the INSRP only provides a risk assessment. It does not evaluate the benefits of a proposed launch, nor does it make any recommendation with respect to whether to launch or not.

With the concurrence of the other two agencies, then, the user agency proposes launch approval to OSTP. Thus, for Galileo and Ulysses NASA would propose launch approval after having obtained concurrence from the Department of Defense and the Department of Energy. Now, the process I briefly described above has been followed with respect to the Galileo and Ulysses missions. Our involvement with these missions began in October 1977. As early as this year, we had essentially completed our nuclear safety review, and were in the process of preparing our SAR.

We were targeting to submit our report to the three agencies by mid-February considering the schedule for a possible launch of the missions in May of this year. This was all changed, of course, by the tragic accident that occurred to the shuttle *Challenger* on January 28 of this year. It is INSRP's position that we must review the results of the ongoing accident investigation before we can make any final nuclear risk assessment for Galileo and Ulysses. Toward this end, we are in the process of requesting information regarding the *Challenger* accident so that we can be better able to determine its implications upon the Galileo and Ulysses nuclear risk assessments.

It is critical in our judgment that engineering assumptions and analyses made regarding the Galileo and Ulysses missions before the *Challenger* accident be reevaluated after the investigation has been completed.

In conclusion, we would like to say we believe that the INSRP process and procedures have worked well over some 22 launches and nuclear systems into space. We believe the process has contributed in a material way to the safety of these launches, and has been a valuable aid in the decisionmaking process. We would like to close this statement by recognizing the dedicated services performed by the chairpersons and the members of our subpanels. The unselfish efforts and expert technical contributions by these persons are the real heart of the INSRP process.

That completes our statement, Madam Chairwoman.

[The prepared statements of Messrs. Gray, Joyce, and Klug follow:]

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STATEMENT BY THE

INTERAGENCY NUCLEAR SAFETY REVIEW PANEL*

BEFORE THE

SUBCOMMITTEE ON ENERGY RESEARCH AND PRODUCTION
AND SPACE SCIENCE AND APPLICATIONS
COMMITTEE ON SCIENCE AND TECHNOLOGY
UNITED STATES HOUSE OF REPRESENTATIVES

MARCH 4, 1986

Madam Chairman, Mr. Chairman, and distinguished members of the subcommittees, we are pleased to have this opportunity to discuss the role of the Interagency Nuclear Safety Review Panel (INSRP) in evaluating the nuclear risks associated with launching space vehicles with nuclear systems abroad.

In our testimony, we will discuss the makeup of the INSRP, the manner in which it functions as a part of the aerospace nuclear safety review process, and the status of our reviews of the Galileo and Ulysses missions. In accordance with your request, this testimony will primarily address the INSRP process and procedures.

BACKGROUND

Presidential Directive/NSC-25 establishes the basic procedure to be followed for launching space nuclear systems. An environmental impact statement or a nuclear safety evaluation report is prepared, and in addition, presidential approval is required for launches of spacecraft utilizing radioactive sources containing a significant quantity of radioactive material.

According to the directive, an ad hoc Interagency Nuclear Safety Review Panel consisting of members from the Department of Defense (DOD), Department of Energy (DOE), and National Aeronautics and Space Administration (NASA) evaluates the risks associated with the mission and prepares a Nuclear Safety Evaluation Report (SER). The Nuclear Regulatory Commission (NRC) is requested to participate as an observer when appropriate. The Environmental Protection Agency (EPA) also is invited as an observer. The head of the sponsoring agency requests the President's approval for the flight through the

*Leven B. Gray, INSRP NASA Coordinator
John P. Joyce (Colonel, USAF), INSRP DOD Coordinator
Norman P. Klug, INSRP DOE Coordinator

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Office of Science and Technology Policy (OSTP). The Director of OSTP is authorized to render approval for such launchings, unless he considers it advisable to forward the matter to the President for decision.

A copy of NSC-25 will be provided to the subcommittees for the record.

The INSRP, established in accordance with this directive, provides an independent evaluation of the risks associated with the launch of a nuclear power system in space. The Panel members are independent of the program and the Panel is organized such that no single agency is dominant. The Panel is an ad hoc organization which is established when a mission utilizing a nuclear power system is being planned. The current Panel was established for nuclear payloads (including Galileo and Ulysses) using the Space Transportation System. The three coordinators in the current Panel are listed in Attachment 1 along with their organizational affiliations.

The Panel is supported by subpanels sponsored by the three agencies. Subpanels are currently organized in the areas of Launch Abort, Reentry, Meteorology, Oceanography, and Biomedical/Environmental Effects. The subpanels are staffed by technical experts in these various disciplines. The current membership of the INSRP subpanels is included in Attachment 2 through 7, along with their organizational affiliations.

The independent safety review process conducted by the Panel has been in place since the mid 60's. The process has been used for review of diverse missions where spacecraft deployment has included earth orbit, lunar surface, Jupiter fly-by/deep space, Mars lander, and Jupiter/Saturn fly-by.

SAFETY REVIEW PROCESS

The aerospace nuclear safety review process is depicted in Attachment 8.

The program's evaluation of the safety aspects of a nuclear power system as associated with a specific space mission is provided via Safety Analysis Reports (SAR's). These reports are the responsibility of DOE and are prepared by the DOE nuclear system contractor. They contain and utilize significant input information which originates from the agencies responsible for the spacecraft, launch vehicle, launch operations, and the launch range. Briefly, an SAR includes a description of the mission and flight system including the appropriate details of the nuclear power system, the spacecraft, launch vehicle, and the flight profile and characteristics. The SAR then develops the potential accident

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environments and response of the nuclear power system to these environments. The SAR then proceeds to describe the resulting potential radiological risks. There is usually a Preliminary Safety Analysis Report (PSAR), an Updated Safety Analysis Report (USAR), and a Final Safety Analysis Report (FSAR).

The Panel meets with the program elements to review the nuclear safety aspects of a proposed mission after the issuance of the PSAR, the USAR, and the FSAR. The Panel and/or the subpanels meet with the program elements on an ad hoc basis during the course of the program as determined by the status of the program activity and the nature of the safety issues at hand. Continuing interaction between the Panel and subpanels with the program assures that the Panel and subpanel personnel are informed of the program events important to nuclear safety while the program is in progress.

When INSRP personnel recognize potential problems, data or information deficiencies, or any other item which may lead to problems during a review, this information is provided to project personnel for action. Participation during the early phases of a project does not, however, commit reviewing personnel to any particular position. An attempt is made to prevent inconsistencies, but if information comes to light at a later date which changes the outlook on a particular problem, the reviewers operate on the latest available data.

After the review of the FSAR and any other germane documents such as test reports and additional analyses provided by the program, the Panel prepares its SER. This report summarizes the Panel's risk evaluation. It is important to emphasize that INSRP only provides a risk assessment. It does not evaluate the benefits of a proposed launch, nor does it make any recommendation with respect to whether to launch or not. With the concurrence of the other two agencies, the user agency proposes launch approval to the OSTP. Thus for Galileo and Ulysses, NASA would propose launch approval after having obtained concurrence from DOD and DOE.

STATUS OF INSRP REVIEWS OF GALILEO/ULYSSES

The process described above has been followed with respect to the Galileo and Ulysses missions. Our involvement with these missions began in October 1977. As of early this year, we had essentially completed our nuclear safety review, and were in the process of preparing our SER. We were targeting to submit our report to the three agencies by mid February, considering the schedule for possible launch of the missions in May of this year.

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This was all changed, of course, by the tragic accident that occurred to the Challenger Shuttle on January 28 of this year. It is INSRP's position that we must review the results of the ongoing accident investigation before we can made any final nuclear risk assessment for Galileo and Ulysses. Towards that end, we are in the process of requesting information regarding the Challenger accident so that we can be better able to determine its implications upon the Galileo and Ulysses nuclear risk assessments. It is critical in our judgment that engineering assumptions and analyses made regarding the Galileo/Ulysses missions before the Challenger accident be re-evaluated after the investigation has been completed.

CONCLUSION

In conclusion, we would like to say that we believe that the INSRP process and procedures have worked well over some twenty-two launches of nuclear systems into space. We believe the process has contributed in a material way to the safety of these launches and has been a valuable aid in the decision making process.

We would like to close this statement by recognizing the dedicated service performed by the chairpersons and members of our subpanels. The unselfish efforts and expert technical contributions by these persons are the real heart of the INSRP process.

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INSRP MEMBERSHIP: COORDINATORS

- DOD (APPOINTED BY ASST TO SEC DEF FOR ATOMIC ENERGY)

  COL. JOHN P. JOYCE
  DEPUTY DIRECTOR
  AFISC DIRECTORATE OF NUCLEAR SURETY

- NASA (APPOINTED BY NASA ADMINISTRATOR)

  MR. LEVEN B. GRAY
  MANAGER FOR NUCLEAR SAFETY
  HQ NASA SAFETY OFFICE

- DOE (APPOINTED BY DOE SECRETARY OF ENERGY)

  MR. NORMAN P. KLUS
  OFFICE OF NUCLEAR SAFETY
  OFFICE OF ENVIRONMENT, SAFETY, AND HEALTH

ATTACHMENT 1

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LAUNCH ABORT SUBPANEL (LASP)

LOUIS J. ULLIAN (CHAIRMAN)
EASTERN SPACE & MISSILE CENTER
ESMC/SEM
PATRICK AFB, FL 32925

ROBERT W. BROWN
JOHNSON SPACE CENTER (NASA)
NASA/JSC/FM
HOUSTON, TX 77058

ROBERT F. FLETCHER
JOHNSON SPACE CENTER (NASA)
NASA/JSC/MP
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JOEL R. REYNOLDS
KENNEDY SPACE CENTER (NASA)
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AF INSPECTION & SAFETY CENTER (DOD)
AFISC/SNA
KIRTLAND AFB, NM 87117

WILLIAM A. RIEHL
MARSHALL SPACE FLIGHT CENTER (NASA)
NASA/MSFC/EH-31
HUNTSVILLE, AL 35802

C. M. SEABOURN
LOS ALAMOS NATIONAL LABORATORY (DOE)
MS-K557
LOS ALAMOS, NM 87545

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ATTACHMENT 2

(CONTINUED)

ROBERT GERRON (ALTERNATE)
KENNEDY SPACE CENTER (NASA)
NASA/KSC/SF-ENG
KSC, FL 32899

JOHN W. MARSHALL
AF ROCKET PROPULSION LAB (DOD)
AFRPL/LKLH/STP24
EDWARDS AFB, CA 93523

LT. BRETT HASWELL
AF WEAPONS LABORATORY (DOD)
AFWL/NTYNS
KIRTLAND AFB, NM 87117

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REENTRY SUBPANEL (RS)

DR. KENNETH SUTTON (CHAIRMAN)
LANGLEY RESEARCH CENTER (NASA)
MAIL STOP 366
HAMPTON, VA 23665-5225

DR. GERALD D. WALBERG (ALT. CHAIRMAN)
LANGLEY RESEARCH CENTER (NASA)
MAIL STOP 367
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DR. WILLIAM H. AILOR
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EL SEGUNDO, CA 90245

1ST LT. DON BLAYLOCK
AIR FORCE WEAPONS LABORAORY (DOD)
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APPLIED PHYSICS LABORATORY
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MR. PETER JAFFE
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DR. ANGUS D. MCRONALD
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ATTACHMENT 4

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METEOROLOGY SUBPANEL (METS)

DR. ROBERT J. KURZEJA (CHAIRMAN)
SAVANNAH RIVER LABORATORY
AIDEN, SC 298080

DR. JEFFERY ANDERSON
MARSHALL SPACE FLIGHT CENTER (NASA)
MSFC/ED-44
HUNTSVILLE, AL 35812

LT. COL. TOM MEYERS
ESMC
PATRICK AFB, FL 32925

MR. BILLIE F. BOYD
ESMC/MER
PATRICK AFB, FL 32925

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ATTACHMENT 5

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OCEANOGRAPHIC SUBPANEL (OS)

DR. CHARLES OSTERBERG (CHAIRMAN)
DOE - ENVIRONMENTAL RESEARCH
DOE/EV-75
GERMANTOWN, MD

DR. NORMAN CUTSHALL
OAK RIDGE NATIONAL LABORATORY
SECTION HEAD - EARTH SCIENCES
P. O. BOX X
OAK RIDGE, TENNESSEE 37831

DR. THOMAS BEASLEY
OREGON STATE UNIVERSITY
DEPARTMENT OF OCEANOGRAPHY
CORVALLIS, OR 97331

DR. VICTOR NOSHKIN
LAWRENCE LIVERMORE NATIONAL LAB
P. O. BOX 808
LIVERMORE, CA 94550

DR. DAVID HAYES
SAVANNAH RIVER NATIONAL LAB. (DOE)
AIKEN, SC 29801

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ATTACHMENT 6

INSRP

BIOMEDICAL & ENVIRONMENTAL EFFECTS SUBPANEL (BEES)

DR. MARVIN GOLDMAN (CHAIRMAN)
UNIVERSITY OF CALIFORNIA
LEHR
DAVIS, CA 95616

DR. RICHARD CUDDIHY
INHALATION TOXICOLOGY RESEARCH INSTITUTE
LOVELACE BIOMEDICAL & ENVIRONMENTAL RESEARCH INSTITUTE, INC.
P. O. BOX 5890
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KSC/MD-ENV
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LT. COL. ROBERT C. NELSON
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AFISC/SHAR
KIRTLAND AFB, NM 87117-5000

MR. JAMES F. PARK
INHALATION TOXICOLOGY, BIOLOGY DEPT.
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DR. JOHN PINDER
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DRAWER E
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ATTACHMENT 7

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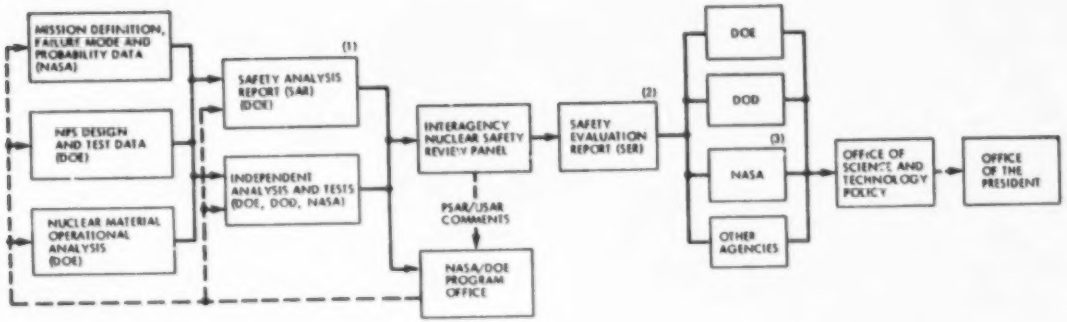
AEROSPACE NUCLEAR SAFETY REVIEW PROCESS



(1) PSAR = PRELIMINARY
USAR = UPDATED
FSAR = FINAL
} SAFETY ANALYSIS REPORT

(2) SAFETY EVALUATION REPORT WRITTEN BY IISRP BASED ON FSAR REVIEW AND INDEPENDENT ANALYSIS

(3) RESPONSIBLE MISSION AGENCY MUST MAKE LAUNCH RECOMMENDATION

ATTACHMENT 8

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Mrs. LLOYD. Thank you very much, Mr. Gray.

Each of you three gentlemen represent organizations that have direct involvement in the Galileo and Ulysses missions on the Shuttle Program in one aspect or another. How do the three of your view yourselves as independent to take care of these missions? You are part of your own organization, yet you operate independently in this panel.

Mr. GRAY. Yes, Madam Chairwoman, I will start, and I will ask my colleagues to render their views.

Mrs. LLOYD. Do you report your activities to your own organization or to OSTP?

Mr. GRAY. Well, both really. I think as the——

Mrs. LLOYD. Which one is the major player, though?

Mr. GRAY. Primarily the purpose of our efforts is to come up with a safety evaluation report which is used by OSTP. It is not subject really to change really by the agencies. It is the panel effort, and it basically becomes the document that is used by the OSTP and their decisionmaking process.

Mrs. LLOYD. Mr. Klug.

Mr. KLUG. I would agree pretty much with what Leven says. I received a letter appointing me to the board, and our job—my job is to prepare the best independent safety evaluation we can. We will then provide that to OSTP and the agency heads, too. That doesn't mean we don't keep my people, the people above me informed of what is going on. And I have briefed them pretty much on what we are doing here today on the process, but we are very independent. We are working for OSTP in the real sense of the word.

Mrs. LLOYD. Colonel Joyce, would you like to comment?

Colonel JOYCE. I probably have the easier answer to the question. Of course, the DOD in this case has no vested interest in either of these missions except from a range safety standpoint. We do have the range safety responsibility at the Eastern Test Range.

As far as any pressures, if you may ask that I have felt, there has been none. I basically feel like I am working for the OSTP. I do keep my management informed of what I am doing because, obviously, they fund me, but I have had no intervention whatsoever, and what I intended to do during this process is when we had completed the SER, I was to give, if you will, the chain of command a courtesy briefing, but they would have no input whether to say yes or no to my report.

Mrs. LLOYD. So the agency that you represent primarily serves the background and the experience that you put into your efforts in reporting.

Colonel JOYCE. I am not sure if I follow your question.

Mrs. LLOYD. Basically you represent the service, isn't that correct?

Colonel JOYCE. That's correct.

Mrs. LLOYD. That's correct. And you represent NASA.

Mr. GRAY. Basically, yes, we are appointed by those three agencies, Madam Chairwoman, but I think we represent the INSRP coordinators. We are an independent review process. Basically we try to manage that process utilizing the expertise of our subpanels to

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come up with the most sound technical assessment we can of the risk associated with this kind of a mission.

Mrs. LLOYD. Well, let me get to what I am really getting at. If this should be a real substantive disagreement between INSRP and, say, NASA, the Department of Defense and the Department of Energy on a safety-related matter related to RTG's, how would you resolve this disagreement?

Mr. GRAY. Well, I believe that what happens is that during the process there are many technical discussions, and perhaps in many cases some disagreements. Those occur within our own subpanels. They occur between the INSRP process and NASA or DOE or the spacecraft people, and those are surfaced. We feel like that really is one of our purposes, and by surfacing them we attempt to gain resolution of them, and we do that really by further discussions or by achieving further analysis or in some cases promoting a test which would resolve the question and provide a technical answer.

Mrs. LLOYD. Mr. Gray, it is my understanding that INSRP disagreed with NASA in their estimate of the failure probability for the SRB; that they felt that magnitude was too low. Now, how was this matter resolved, or was it resolved?

Mr. GRAY. Well, Madam Chairwoman, really our report is the culmination of a lot of efforts, and it is not unusual—in this particular case, we have been involved in this since 1977, not personally, perhaps, but at least the process has been going on. During that period of time there are many occasions where disagreements or questions are raised. And it may take some time to resolve those, as a test may be set up and the time required to accomplish that test in pursuit of the answer.

Sometimes we end up with an agreement to disagree. We simply have no resolution.

Mrs. LLOYD. Well, INSRP did disagree with NASA.

Mr. GRAY. At that point in time, but you see, that is only a point in time, and may not represent our final assessment, but certainly at that point in time we did disagree.

Mrs. LLOYD. And was it resolved?

Mr. GRAY. It has not been resolved at this point. I think our report has not really been written because we still have it open. Our final conclusion, therefore, has not been established yet. Obviously, the information in the shuttle data book pertaining to this particular event, as Dr. Silveira testified, is going to be looked at and reevaluated. That will, perhaps, reflect a change in the shuttle data book.

The Department of Energy will then use the change in that data book to review their activities in terms of the RTG. We will then, as an independent reviewer, review those changes and draw conclusions from them. But at this point, that whole process has yet to be accomplished, and the results of that would be somewhat premature.

Mrs. LLOYD. Turning to another area, Mr. Gray, has the Launch Abort Safety Panel, which I understand reports directly to you—isn't that correct?

Mr. GRAY. Yes.

Mrs. LLOYD. Do they have any comments on the Teledyne report or the Sandia studies relative to their methodology or their validity?

Mr. GRAY. Madam Chairwoman, that event really occurred prior to my being appointed to NASA, and I think Colonel Joyce is probably the closest in time to that event, and I would like him to address it.

Mrs. LLOYD. We would like to hear from you, Colonel.

Colonel JOYCE. Yes, Madam Chairwoman, I would like to address that and kind of put it in perspective. Originally there was a report, the Wiggins report whose purpose was not necessarily for nuclear safety, but was to address what the effect would be if the range destruct system on the shuttle was not used, and in that report, there were probability numbers given on the SRB failures.

Mrs. LLOYD. That's correct.

Colonel JOYCE. And they varied in the neighborhood of 10 to the minus 3 to 10 to the minus 4.

Mrs. LLOYD. But then when it was decided that you should look at it again, was when the Teledyne report was commissioned.

Colonel JOYCE. Well, what happened then, as a result of the Wiggins report, our Launch Abort Subpanel of INSRP had some concerns whether that report being that was primarily to look at range destruct action, was inadequate for a nuclear safety evaluation concept. As a result, the Air Force Weapons Laboratory, in support of the DOD coordinator, requested Teledyne to look at that Wiggins report and come up with their conclusions.

As a result, the Launch Abort Subpanel looked at both reports, both the Wiggins report and the Teledyne report and realized that it is really not that much difference. Typically in analysis an order of magnitude is not unknown. It is quite likely to occur. Based upon that, they saw no reason to pursue either report any further.

Consequent to that, the weapons lab then had Sandia to do their report and what happened at that point was immediately after publication of the Sandia report, is when NASA came out with a new shuttle data book, which showed the reliability of the solids to be very high. So rather than waste our efforts on the other three previous reports, the Wiggins report, the Teledyne and the Sandia, we elected to work with NASA on these very high reliability numbers for the solids, so that is the reason why it was not pursued any further.

Mrs. LLOYD. They didn't look at the findings or the results any further. They are going to look at the new data, then.

Colonel JOYCE. I'm sorry?

Mrs. LLOYD. Then you are not going to look at the conclusions of the Teledyne or the Sandia studies.

Colonel JOYCE. Well, the Launch Abort Subpanel did look at those, but the point being is rather than put our efforts into that, we better put our efforts into these high reliability numbers on the SRB's reflected in the shuttle data book because that is even farther more reliable than historical has shown, so it is just a matter of conservation of resources.

We felt it was more appropriate to spend our time working with NASA on the shuttle data book to understand how they came up with such high reliability numbers.

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Mrs. LLOYD. In other words, the new, updated shuttle data book is going to have precedence over the Teledyne or the Sandia studies.

Colonel JOYCE. Well, the point being on that is those numbers used in the shuttle data book are used by the Department of Energy in their FSAR's, in their safety analysis report. And we had a little trouble with the Wiggins report and the Teledyne as far as the reliability numbers of the solids, but when you came up with maybe two orders of magnitude and more reliable, we thought it is best to concentrate on an even bigger problem, and that is why is it that the reliability solids are so great. So it is just a matter of what we put our efforts into.

Mrs. LLOYD. So you will not use the Teledyne or the Sandia studies, then.

Colonel JOYCE. Well, we are aware of them, and we will use them to the extent possible, but INSRP itself will really do its own independent probability, if you will, of the solids failing, and much of the input will be from the historical, what NASA says, what Teledyne says and what Sandia says, and we will come to our own conclusions.

Mrs. LLOYD. In effect, this will be another study.

Colonel JOYCE. Well, we do not do an independent study ourselves. We will factor all of these studies in our safety evaluation report to come up with our probabilities on what the failure rate for the solids are.

Mrs. LLOYD. Well, your report in fact, though, Colonel, would be another study, would it not?

Colonel JOYCE. Well, our study will be a continuation of the study that we are currently involved in.

Mrs. LLOYD. Thank you very much. Mr. Nelson? Excuse me. Mr. Morrison.

Mr. MORRISON. The three of you, as I understand it, have equal weighting as far as the panel is concerned. Two lesser players are involved, the Nuclear Regulatory Commission, and the Environmental Protection Agency.

How have you sensed that they have fit into the process? Have they been active players or are they just interested in reading what conclusions you come up with?

Mr. GRAY. Well, sir, the Presidential directive does indicate that the Nuclear Regulatory Commission shall be invited to participate as an observer. We are conscientiously trying to make that happen, and make sure they are invited to the meetings, especially those keystone or significant meetings. The Environmental Protection Agency has by precedent also been invited to participate.

Both of them are very passive in their roles. I cannot speak entirely for them in terms of their perspective, but basically they do appear at our major meetings, and observe the process, but basically remain in pretty much of a passive role.

Mr. MORRISON. They have not gone overboard in expressing concerns about some things we have heard today such as the potential release of some plutonium in case of a major disaster on the launch pad, that sort of thing?

Mr. GRAY. No, sir, I think their purpose is to assure that an adequate evaluation risk assessment is accomplished. They are observ-

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ers really to the INSRP process, and of course we have no report yet, so it would be premature for them to take a position in that regard. But, no, they have not expressed great concern. They have been, as I say, relatively passive in observing the process.

Mr. MORRISON. How far forward do you look? We know the Department of Energy is doing some very exciting things in development of next-generation devices, including the SP-100, which is an actual nuclear reactor going into space. Have you started work in evaluation of those machines and whether they in fact are different in concern than the machines we have now, strictly isotopes and thermoelectric generation?

Colonel JOYCE. Yes, sir, on two previous occasions in the last couple of years we have had informal discussions with the SP-100 program. The big problem of it was prior to that point, there was no mission per se, and normally INSRP gets involved when there is a mission for a particular type of a nuclear power source.

However, discussions with the program, we had planned to, in early February or March, after we had originally thought we would complete the Galileo/Ulysses launch to draw up a type of an agreement between the SP-100 program and INSRP so that we can formalize how the INSRP will interact the SP-100 program. So, yes, sir, we are involved.

Mr. MORRISON. You have a whole new set of problems with the nuclear reactor in space

Colonel JOYCE. It will be a different type of problem. Of course, the shuttle will be the shuttle, and the accident scenarios will probably be typical of what we might expect for Ulysses/Galileo, but the consequences may be different because we do have a different animal with our reactor as opposed to an RTG.

Mr. MORRISON. Thank you, Madam Chairman.

Mrs. LLOYD. Thank you, Mr. Morrison.

Mr. Nelson.

Mr. NELSON. It is my understanding that you all were getting ready to advise the White House on whether or not we ought to fly in May.

Mr. KLUG. I don't think that is quite correct, sir, because as our statement said, we make a risk evaluation. We do not make any recommendation one way or another on the launch.

Mr. NELSON. OK, you were getting ready to advise the White House on your risk evaluation.

Mr. KLUG. Correct.

Mr. NELSON. And that was about a week away. And then we had the *Challenger* tragedy. What was your advice on the risk evaluation?

Colonel JOYCE. At what point, sir? At the time the accident occurred?

Mr. NELSON. That's correct. On or about January 28, you all were getting ready to advise as to an upcoming event—two events, Galileo and Ulysses What was your risk evaluation?

Colonel JOYCE. At that point we had not completed it, and to this date we still have not.

Mr. NELSON. You were 1 week away from advising the White House, weren't you?

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Colonel JOYCE. No, sir. This was the 28th. We had planned to brief the NASA Administrator on the 18th of February.

Mr. NELSON. So you were 2 weeks, 2½ weeks away.

Colonel JOYCE. Yes, sir.

Mr. NELSON. What was your evaluation at that point?

Colonel JOYCE. We had not actually completed it. We were in a very time-compressed schedule for the development of the SER.

Mr. NELSON. You don't have any clues as to what your recommendation was going to be?

Colonel JOYCE. We had some general thoughts, yes, sir.

Mr. NELSON. OK, general thoughts. What were they?

Colonel JOYCE. Unfortunately, the results of the FSAR has not been briefed, but by and large—and I will just do it kind of qualitative in nature, because we didn't really arrive at our exact numbers, but I will give it to you in a qualitative manner.

When you see the FSAR results, we felt that in general there was higher probability of the accident occurring, slightly larger source terms, but the overall consequences were about the same.

Mr. NELSON. Now what do source terms mean?

Colonel JOYCE. Source term is the amount of plutonium 238 that would be released.

Mr. NELSON. So you are saying higher probability of accident, but what with regard to the source?

Colonel JOYCE. A slightly higher source term. Given that an accident occurs, then you will have what you call a source term or a release of plutonium. We would normally have slightly more plutonium released than what was considered in the FSAR, but during our analysis we use what we call a de minimis concept, which below a certain millirem of radioactive material, there was really no consequences. And this is pretty much an accepted practice now. The consequences would actually be, as far as the risk assessment is about, what the FSAR reflected.

Mr. NELSON. Refresh my memory. What was that?

Colonel JOYCE. As far as the consequences? Sir, that will be briefed in the closed session.

Mr. NELSON. All right. And FSAR stands for what again?

Colonel JOYCE. Final safety analysis report.

Mr. KLUG. I might hasten to add, too, that as our statement said, once we see the results of the *Challenger* investigation, then we will take another look at the whole thing. So he is talking pre-*Challenger* accident.

Mr. NELSON. OK, let's talk about these reports here again. These things are going to get worn out by me just holding them up.

We have got the Teledyne, and we had the Wiggins, and then Sandia looked at both of those. Now, you had talked with Mrs. Lloyd about this, and what are you saying, that you all don't really look at as authentic any one of these reports in coming to your own conclusions?

Colonel JOYCE. In any analysis where you have four different opinions, you may say one is right or none are right. We consider those all inputs to our safety evaluation report, and I must say that normally, for example, the area of solids we rely more heavily on the historical data.

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Mr. NELSON. And I think that is reasonable. And you agree, as the earlier witness did, I guess it was NASA's chief engineer that your place of more probable failure would be the SRB's.

Colonel JOYCE. That's correct, sir.

Mr. NELSON. For your statistical data standpoint.

Colonel JOYCE. Yes, sir.

Mr. NELSON. OK, that being the case did you come up with a number about 1 in 1,000?

Colonel JOYCE. I would say just to keep it general, on the order of 1 to 1,000 or so, something of that ball park.

Mr. NELSON. Can you figure out why in the world, and the question is why—not in the world, why—why there is such a great variance with what NASA has said here today which is 1 in 100,000?

Colonel JOYCE. We talked with NASA on several occasions on that subject, sir, and one must consider also something that the shuttle does have going for them that the older system doesn't. One is that you are further up on the learning curve, in which you have got more experience under belt, more solids that have been launched.

Another factor is the solids are recoverable. That is unprecedented in previous solid rocket booster launches. However, we felt—INSRP felt we couldn't still stretch the historical to 10 to the minus 5, so there was still a divergence of opinion.

Mr. GRAY. I believe, as Dr. Silveira stated, this number of NASA's was a design number, one that they were striving to achieve. And what we had used as data base by our launch abort subpanel was basically, as Colonel Joyce indicated, a historical number going back over some 20 years perhaps.

Mr. NELSON. With regard to the unmanned——

Mr. GRAY. With using large solid rocket motors, and then trying to apply some engineering judgment on top of that as to looking at the circumstances of those to arrive at a proper assessment of what that ought to be and I think it is important to say that historically, and the way a safety evaluation is performed, the softer your data the more conservative you attempt to be, and the better your data the more you can use that data point. And so our launch abort subpanel, where we have this type of expertise, has to include all available information—the reports you cited were certainly used by them, and their work would be weighted in terms of value with the other information available to them.

They in turn will then weigh all that information and assess a number, which they will recommend on up to the panel, and when you asked the question about what we were doing on or about January 28, we were trying to make the orchestra play together, the three of us, frankly, and we had inputs from our five subpanels, and we were trying to look at that, and those were derived fairly independently. We were trying to look at those and make sure that they all fit together into this final report we were producing, and the orchestra did in fact play together.

Mr. NELSON. OK, now when the orchestra played, it played to the tune of 1 in 1,000.

Mr. GRAY. The recommendation that we were dealing with from our subpanel was in that neighborhood; that's correct.

Mr. NELSON. Then the question is, would the risk levels be acceptable in using the space shuttle with carrying RTG's?

Mr. GRAY. That is not a decision that we would make. What we would be doing in our assessment—I think this is the point Mr. Klug was trying to make. Our purpose is not to make a recommendation of what is safe or unsafe. Our purpose is to provide the best technical base that we possibly can to aid the decisionmaker in that decision, and he will factor in additional information in addition to our report; things that we are not even attempting to assess, but we want to provide that basic technical data point for him, but not recommend.

Mr. NELSON. I know, but you are also a human being. You have got some feelings. Do you have a feeling one or another?

Colonel JOYCE. I would put it this way, sir, if I had been invited to the launch, I would have attended.

Mr. NELSON. You would have launched.

Colonel JOYCE. If I was invited to the launch to observe it, I would attend.

Mr. NELSON. Would you have crawled in the orbiter?

Colonel JOYCE. I am no longer in flying status, sir.

Mr. NELSON. Neither am I.

Well, you see what our problem is here, we have got to sort through all of this. Sometimes it is like pulling teeth to get you all to give some answers, but we have got to sort through all of this stuff and determine what is in the public interest.

Mr. GRAY. I think it is important that we try to provide that kind of information too, and let me describe, as has been done and maybe overlooked, several statements that the information in this type of analysis is perhaps only good plus or minus one order of magnitude. Therefore, if one were on the optimistic side of that, the upper end of it, versus being on the pessimistic side of it, you would be two orders of magnitude difference, but still dealing with the same data point. All right, sir? If that helps in putting it in perspective.

Mr. NELSON. OK. Anything else that you all can think of that should have been done to the shuttle or the RTG's to make it safer?

Colonel JOYCE. I believe, sir, there has been a couple of things that have been tossed around as ideas, and the three of us are aware of those ideas. If we had any further ideas, we would pass those to the program.

Mr. NELSON. Anybody else?

Mr. KLUG. I think we have already heard from the program, both NASA and DOE that they are going to be looking at other things, and in the review mode we will look at what they have to say, question them, that sort of thing.

Mr. NELSON. Do you have any opinion about the blast overpressure? Do you have any variance of opinion with what we have heard here today about the blast overpressure and its design, and the various scenarios with and without the Centaur in it and so forth?

Colonel JOYCE. I think the three of us have no opinion at this point. I think it is premature. I think we prefer to wait. We have put together a letter that is going to the Presidential Commission

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asking for any data that we can obtain. Primarily we are interested in if we can come up with overpressure that occurred, any shrapnel distribution that occurred, temperatures.

At this point, I think from the coordinators' standpoint we would only be guessing, sir.

Mr. NELSON. When you were back on flying status, Colonel, did you all used to have the guys who packed parachutes, have to take the parachutes out every now and then and jump out?

Colonel JOYCE. No, sir, we didn't. We had confidence in our people.

Mr. NELSON. I am wondering if maybe we ought to try that with the lottery system here sometime from time to time.

All right, thank you, Madam.

Mrs. LLOYD. One other question: when you do get all your other information assembled, would you report back to this committee since this is a little bit premature; that you are still compiling information. When you get all of your information in, will you provide that information to this committee?

Mr. GRAY. Madam Chairman, we normally would be pleased to do that. My schedule will be driven by the rescheduling of those two flights, and they have not been rescheduled yet, so I don't know how our schedule is going to be.

Mrs. LLOYD. We would like to share this information with you if it is possible. Mr. Walker.

Mr. WALKER. Thank you, Madam Chairman.

Do I understand correctly that there is not much more you can do in terms of establishing information until we hear back from the *Challenger* investigation; that that is intricate to your establishing your final base lines now and so on?

Mr. GRAY. Congressman, we believe that to be the obvious pertinent data point. We think the assumptions that have been made up to date should be reviewed in regard to the physical evidence that has been recovered, and the analysis that has been done, and it is either going to verify what we have said previously, or it is going to shed new light on the situation.

Mr. WALKER. And so anything that is done to delay that investigation, in fact delays your investigation, and in fact delays what you are able to do in terms of establishing safety in a nuclear program; is that correct?

Mr. GRAY. I think it will delay us achieving the best answer possible.

Mr. WALKER. I must say that we are in the same kind of situation ourselves in that there is not very much we can do with regard to the shuttle program per se until we get that kind of investigation, and I find somewhat disturbing a letter that I have here from NASA, and, Mr. Gray, you may want to confirm whether or not this letter in fact presents the fact that you know them that indicates that as a result of requests of a subcommittee of fairly questionable jurisdiction in the particular area that we are dealing with here, that the task force supporting the investigation of *Challenger* has had to be robbed of personnel—personnel have had to be reassigned to answer questions relative to this one Member of Congress posing those particular questions of NASA.

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Is that your understanding of what is taking place down there right now; that we in fact have had an investigation of great national import undermined by one Member asking questions; that NASA has had to pull people off that investigation and assign them to answer those questions?

Mr. GRAY. Well, sir, I don't know if I can address that specifically. It is a very busy time for us.

Mr. WALKER. Well, I quote from the letter,

> The quantity and the broad scope of the questions has required the reassigning the personnel from NASA's Data and Design Analysis Task Force supporting the *Challenger* accident investigation. These people and others are diligently researching the remaining questions.

So, in fact here is a NASA letter that states specifically that people have had to be pulled off the *Challenger* investigation in order to research these questions. Is it typical that NASA does pull people off investigations of major national import in order to answer the questions of one Member of Congress?

Mr. GRAY. Sir, I think you probably best address that question to our NASA management, I respectfully submit.

Mr. WALKER. Well, you are probably the wrong one to ask. You are indebted to NASA and so on, but I must say I am really disturbed by this information. That is not your problem. I think it is a problem that accrued from Capitol Hill, but I think in light of what we are doing here, it needs to be understood that there at least some Members of Congress who at this point are having an adverse impact on achieving precisely the kinds of information that will allow you to move forward, and allow us to forward.

Mrs. LLOYD. Would the gentleman yield?

Mr. WALKER. I would be glad to yield to the chairwoman.

Mrs. LLOYD. I thank the gentleman for yielding. I was wondering if you would like to ask Mr. Silveira—Dr. Silveira to come to answer your question.

Mr. WALKER. If Dr. Silveira would have an answer to that question, I would be very pleased to hear from him on it.

Mrs. LLOYD. Dr. Silveira, you are back on the stand. You should have gone out the door while you had a chance.

Dr. SILVEIRA. As you have stated, there are many requests on us to answer and get back with—waivers, critical items lists, an awful lot of things. Indeed, we have had to take people off of the work they are currently doing, looking at the actual investigation to service these requests to do it in a time period that we have been asked to do it in.

Mr. WALKER. And I think that that is understandable. I think that most people here would understand why people would have to be taken off current assignments in order to do the investigation on *Challenger*. I mean, I think that is understandable.

What I am concerned about now is it appears as though that people have had to be taken off the *Challenger* investigation in order to answer question from at least one Member on Capitol Hill. Is that your understanding?

Dr. SILVEIRA. Yes, sir, because I have been closely involved with the accident investigation as far as *Challenger* is concerned, and before any of those answers, and a lot of them are obtained by my

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office. I will have to spend time going over those and make sure they are correct before they are forwarded.

Indeed, some of the people—and we have almost our entire staff, at least as far as the headquarters staff is concerned, in some aspect of the investigation, and indeed we are going to have to reassign them to service this request as compared to being able to work on *Challenger*.

Mr. WALKER. Well, I thank you for being direct with us, and I personally think it is a damn shame, and, thank you, Madam Chairwoman. I yield back.

Mrs. LLOYD. Thank you, Dr. Silveira.

Dr. SILVEIRA. Thank you.

Mrs. LLOYD. And thank you, Mr. Walker.

Thank you for appearing before the committee. Oh, Mr. Fawell.

Mr. FAWELL. I have no questions.

Mrs. LLOYD. Thank you for being with us.

We welcome our next panel which includes Mr. Giles Sinkewiz, who is general manager of General Electric Space Systems Operation, as well as Mr. Peter Vogelberger, who is president of Teledyne Energy Systems. Welcome, gentlemen. We have your testimony, and you may proceed as you wish. You may summarize. Your entire statement will be made a part of the record. Mr. Sinkewiz, please proceed.

STATEMENT OF GILES C. SINKEWIZ, GENERAL MANAGER, GENERAL ELECTRIC SPACE SYSTEMS OPERATION, AND PETER J. VOGELBERGER, JR., PRESIDENT, TELEDYNE ENERGY SYSTEMS

Mr. SINKEWIZ. Good afternoon. Thank you, Madam Chairwoman and Mr. Chairman and members of the subcommittees. I would like to summarize my testimony.

I would like to summarize the previous space applications of RTG's in which General Electric has participated and describe our safety analysis work for the generators plan for the use in the upcoming Galileo and Ulysses missions. Since 1961, there have been 23 launches of spacecraft involving one reactor and 38 RTG's as power sources. We have participated in 11 of these missions: 2 for the NASA Nimbus Program, a spacecraft contractor and RTG integrator.

For the other missions we have developed and produced 16 flight RTG's. One important element of the SNAP-27 RTG Program was the design of safe heat source for manned mission involving Saturn V. These safety features were put to test on the Apollo 13 mission. A failure in another spacecraft subsystem resulted in an abort of the mission and return of the astronauts. The heat source performed as designed by surviving reentry into the Earth's atmosphere.

Rigorous design and analysis approaches were also applied in the development of the RTG's for the upcoming Galileo and Ulysses missions. Since its inception, the U.S. Space Nuclear Power Program has placed great emphasis on the safety of people and the protection of the environment. A continuing primary objective has been to prevent to undue risk by designing the systems to contend

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the isotope fuel safely under normal and potential accident conditions. We are fully committed to this objective at GE.

The Department of Energy has conducted an extensive safety analysis and test program in direct support of the development of the RTG's for Galileo and Ulysses The safety analysis is documented by a series of reports. Preliminary safety analysis reports were issued in 1979 and in 1980 in the early stages of power system development. An updated safety analysis report was issued in 1984. The final safety analysis report was published in 1985 as fabrication and testing of the flight power generators were completed.

These reports and results of the safety test program have been made available to INSRP for the use and development of their independent safety evaluation. INSRP and others in the safety community furthermore have provided critical review at each step in the development of these safety reports and our comments have incorporated into FSAR. The analysis GE has conducted for the FSAR is based upon potential launch vehicle aborts, failure probabilities, and environments defined by NASA.

This information is provided in a NASA controlled document commonly referred to as a Shuttle Data Handbook. These potential aborts, probabilities and environments are defined for several phases of the launch processes, including pre-launch, first stage ascent, second stage ascent, orbit and insertion. The results of the abort/sequence analysis are expressed as a list of fuel releases associate probabilities named source terms. Each source term is characterized by magnitude, location, and particle size of fuel release.

Some of the possible events calculated can in fact result in release of fuel. The NUS risk analysis show extremely low probability of danger to health compared to everyday risk. I believe that a very comprehensive analysis of RTG safety for the Galileo and Ulysses missions have been accomplished. I believe that the results obtained represent a conservative assessment of RTG safety.

That concludes my results.

[The prepared statement of Mr. Sinkewiz follows:]

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SUBCOMMITTEE ON ENERGY RESEARCH AND PRODUCTION

CHAIRPERSON MARILYN LLOYD

SUBCOMMITTEE ON SPACE SCIENCE AND APPLICATIONS

CHAIRPERSON BILL NELSON

TESTIMONY BY

MR. GILES C. SINKEWIZ, GENERAL MANAGER
SPACECRAFT OPERATIONS
GENERAL ELECTRIC COMPANY
KING OF PRUSSIA, PENNSYLVANIA

MARCH 4, 1986

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GOOD AFTERNOON MADAM CHAIRMAN, MR. CHAIRMAN, MEMBERS OF THE SUBCOMMITTEES AND DISTINGUISHED GUESTS. I AM GILES SINKEWIZ, GENERAL MANAGER OF SPACECRAFT OPERATIONS FOR THE GENERAL ELECTRIC COMPANY. IT IS MY PRIVILEGE TO HAVE THIS OPPORTUNITY TO PRESENT MY VIEWS ON THE CRITICAL SUBJECT OF SAFETY IN THE USE OF RADIOISOTOPE ELECTRIC POWER GENERATORS FOR SPACE APPLICATIONS.

THE GENERAL ELECTRIC COMPANY HAS PARTICIPATED EXTENSIVELY IN DOE'S LONG AND SUCCESSFUL PROGRAM OF DEVELOPMENT AND DEPLOYMENT OF THESE GENERATORS. GE, FURTHERMORE, IS CURRENTLY A MAJOR CONTRACTOR TO DOE FOR THE FABRICATION AND SAFETY ANALYSIS OF GENERAL PURPOSE HEAT SOURCE RADIOISOTOPE THERMOELECTRIC GENERATORS PLANNED FOR USE IN NASA'S UPCOMING GALILEO AND ULYSSES INTERPLANETARY SCIENCE MISSIONS.

I WOULD LIKE TO SUMMARIZE PREVIOUS SPACE APPLICATIONS OF RADIOISOTOPE GENERATORS IN WHICH GENERAL ELECTRIC HAS PARTICIPATED, AND DESCRIBE OUR SAFETY ANALYSIS WORK FOR THE GENERATORS PLANNED FOR USE IN THE UPCOMING GALILEO AND ULYSSES INTERPLANETARY SCIENCE MISSIONS.

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HISTORY OF SPACE RTG DEPLOYMENT

SINCE 1961, THERE HAVE BEEN 23 LAUNCHES OF SPACECRAFT INVOLVING ONE REACTOR AND 38 RADIOISOTOPE THERMOELECTRIC GENERATORS (RTGs) AS PRIMARY OR AUXILIARY POWER SOURCES. WE HAVE PARTICIPATED IN ELEVEN OF THESE MISSIONS; TWO FOR THE NASA NIMBUS PROGRAM AS SPACECRAFT CONTRACTOR AND RTG INTEGRATOR. FOR THE OTHER MISSIONS, WE DEVELOPED AND PRODUCED 16 FLIGHT RTGs.

EACH OF THE RTGs IS CONSTRUCTED IN A SIMILAR MANNER WHERE A HEAT SOURCE, USING ISOTOPE FUEL, IS SURROUNDED BY A THERMOELECTRIC CONVERTER, WHICH TRANSFORMS A PORTION OF THE HEAT INTO ELECTRICITY. GENERAL ELECTRIC HAS BEEN AT THE FOREFRONT OF RTG TECHNOLOGY FOR MORE THAN 20 YEARS IN BOTH HEAT SOURCE DESIGN AND THERMOELECTRIC DEVELOPMENT. BY VIRTUE OF GENERAL ELECTRIC'S ROLE AS SUPPLIER OF SPACE POWER FOR THE NASA APOLLO, VOYAGER AND GALILEO MISSIONS, THE ESA ULYSSES

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MISSION AND THE DOD LINCOLN EXPERIMENTAL SATELLITES MISSION, WE HAVE GAINED RECOGNITION AS A COMPANY GREATLY CONCERNED WITH NUCLEAR SAFETY. THIS EXPERTISE HAS BEEN CONFIRMED BY THE GOVERNMENT'S APPROVING THE LAUNCH OF 16 GE RTGS TO DATE.

OUR FIRST MAJOR ACCOMPLISHMENT WAS IN THE DEVELOPMENT OF THE SNAP-27 RTGS FOR THE APOLLO PROGRAM. THESE RTGS SUPPLIED THE POWER FOR THE FIVE APOLLO LUNAR SURFACE EXPERIMENT PACKAGES PLACED ON THE MOON BY THE APOLLO ASTRONAUTS. THE PACKAGES GATHERED SCIENTIFIC DATA FOR MANY YEARS ABOUT THE LUNAR SURFACE CONDITIONS, WHICH WERE TRANSMITTED BACK TO EARTH FOR ANALYSIS.

ONE IMPORTANT ELEMENT OF THE SNAP-27 RTG PROGRAM WAS DESIGN OF A SAFE HEAT SOURCE FOR A MANNED MISSION INVOLVING THE SATURN V, THE MOST POWERFUL LAUNCH VEHICLE USED UP TO THAT TIME. THESE SAFETY FEATURES WERE PUT TO THE TEST ON THE APOLLO 13 MISSION. A FAILURE IN ANOTHER SPACECRAFT SUBSYSTEM NECESSITATED ABORT OF THE MISSION AND RETURN OF THE ASTRONAUTS. THE HEAT SOURCE PERFORMED AS DESIGNED BY SURVIVING REENTRY INTO THE

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EARTH'S ATMOSPHERE AND REMAINING INTACT UPON ENTERING THE PACIFIC OCEAN. THIS IS ONLY ONE EXAMPLE OF THE EFFECTIVE AND SAFE RTG DESIGN EMPLOYED BY GENERAL ELECTRIC AND THE NUCLEAR POWER COMMUNITY.

RTG SAFETY WAS ALSO DEMONSTRATED IN EARLIER SPACE MISSIONS INVOLVING RTGS DEVELOPED BY ANOTHER COMPANY. THE LAUNCH OF A TRANSIT SATELLITE, USING A SNAP 9A RTG AS ITS POWER SOURCE, WAS ABORTED AFTER REACHING A HIGH ALTITUDE OVER THE SOUTH POLE. THIS RESULTED IN A STEEP ANGLE REENTRY OVER THE MOZAMBIQUE CHANNEL. THE SNAP-9A RTG SAFELY BURNED UP ON REENTRY, AS IT WAS DESIGNED TO DO. THE NIMBUS B-1 SPACECRAFT, CARRYING TWO SNAP-19 RTGS, WAS DESTROYED BY THE RANGE SAFETY OFFICER 120 SECONDS INTO THE LAUNCH SEQUENCE. THESE RTGS SURVIVED THE EXPLOSION INTACT AS THEY WERE DESIGNED TO DO. THEY FELL INTO THE SANTA BARBARA CHANNEL, AND WERE RECOVERED FROM A DEPTH OF ABOUT 600 FEET. ALL THREE OF THESE FAILED MISSIONS WERE ABORTED SAFELY ACCORDING TO DESIGN CRITERIA.

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Rigorous design and analysis approaches were also applied by General Electric in the development of safe RTGs for the Voyager and LES 8/9, as well as the upcoming Galileo and Ulysses missions. The Voyager spacecraft, using Multi Hundred Watt (MHW) RTGs in encounters with Jupiter, Saturn and Uranus, have provided our scientific community with valuable data to help us understand what processes have shaped the solar system and our own Earth. Clearly, the use of RTGs as the power source has provided a key enabling technology. The DOD Lincoln Experimental Satellites 8 & 9 also benefitted from the use of MHW-RTGs. These communication satellites remain fully operational after almost 10 years of operation.

The power supplies to be employed in the Galileo and Ulysses missions are the General Purpose Heat Source (GPHS) RTGs. This unit, shown in Figure 1 attached to my testimony, uses the same thermoelectric technology as the MHW-RTG, and an improved heat source design. The heat source developed and

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SELECTED FOR THIS RTG IS DESIGNATED AS THE GENERAL PURPOSE HEAT SOURCE. BEING MODULAR IN DESIGN, THE GPHS PROVIDES AN EVEN GREATER MARGIN OF SAFETY THAN THE EARLY SINGLE, LARGE ISOTOPE HEAT SOURCES.

THE HEAT SOURCE IS A BRICK-SHAPED UNIT WITH SPECIAL FEATURES TO PROVIDE RESISTANCE TO MANY ADVERSE ABORT CONDITIONS. THESE CONDITIONS INCLUDE REENTRY AND SUBSEQUENT IMPACT, EXPOSURE TO PROPELLANT FIRES, EXPLOSIVE SHOCK OVERPRESSURE AND HIGH VELOCITY FRAGMENTS. THE ISOTOPE FUEL IS ENCAPSULATED BY IRIDIUM, FORMING AN ASSEMBLY CALLED THE FUEL CLAD. FOUR FUEL CLADS ARE SURROUNDED BY TWO LAYERS OF A GRAPHITE COMPOSITE, FORMING AN ASSEMBLY CALLED HEAT SOURCE MODULE, WHICH IS CAPABLE OF ORBITAL REENTRY WITHOUT DAMAGE. THE IRIDIUM AND GRAPHITE HAVE VERY HIGH TEMPERATURE CAPABILITY. THESE FEATURES PROVIDE GOOD RESISTANCE TO FIRE, EXPLOSION, REENTRY AND IMPACT. FIGURE 2 ATTACHED TO MY TESTIMONY ILLUSTRATES THE HEAT SOURCE DESIGN FEATURES.

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SINCE ITS INCEPTION, THE U.S. SPACE NUCLEAR POWER PROGRAM HAS PLACED GREAT EMPHASIS ON THE SAFETY OF PEOPLE AND PROTECTION OF THE ENVIRONMENT. A CONTINUING PRIMARY OBJECTIVE HAS BEEN TO PREVENT UNDUE RISKS BY DESIGNING THE SYSTEMS TO CONTAIN THE ISOTOPE FUEL SAFELY UNDER NORMAL AND POTENTIAL ACCIDENT CONDITIONS. WE ARE FULLY COMMITTED TO THIS AT GENERAL ELECTRIC.

LAUNCH APPROVAL PROCESS

THE FLIGHT SAFETY APPROVAL PROCESS GOVERNING LAUNCH OF SPACECRAFT EMPLOYING RADIOISOTOPE THERMOELECTRIC GENERATORS IS COMPREHENSIVE AND THOROUGH. THE APPROVAL REQUIREMENTS, DEFINED BY PRESIDENTIAL DIRECTIVE, INCLUDE PREPARATION OF A SAFETY EVALUATION REPORT (SER), WHICH FORMS PART OF THE BASIS FOR A LAUNCH DECISION BY THE PRESIDENT OR BY THE DIRECTOR OF THE PRESIDENT'S OFFICE OF SCIENCE AND TECHNOLOGY POLICY (OSTP). THE SER IS PREPARED BY THE INTERAGENCY NUCLEAR SAFETY REVIEW PANEL WHICH IS AN INDEPENDENT BODY INCLUDING REPRESENTATIVES FROM THE NASA, DOE AND DOD. THE INSRP INCLUDES SUB-PANELS

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WHICH PROVIDE INDEPENDENT INPUT IN THE SEVERAL FIELDS OF EXPERTISE REQUIRED BY THE SER, AND INSRP ARRANGES FOR ITS OWN CONTRACTOR SUPPORT AS REQUIRED.

LETTERS OF CONCURRENCE FROM BOTH THE DOD AND THE DOE ARE PROVIDED TO OSTP, ALONG WITH THE SER WHEN NASA'S REQUEST FOR LAUNCH APPROVAL IS MADE.

PROJECT SAFETY REPORTS AND ANALYSIS

THE DEPARTMENT OF ENERGY HAS CONDUCTED AN EXTENSIVE SAFETY ANALYSIS AND TEST PROGRAM IN DIRECT SUPPORT OF THE DEVELOPMENT OF THE RTGS FOR GALILEO AND ULYSSES. THE SAFETY ANALYSIS IS DOCUMENTED BY A SERIES OF REPORTS. PRELIMINARY SAFETY ANALYSIS REPORTS WERE ISSUED IN 1979 AND 1980 IN THE EARLY STAGES OF POWER SYSTEM DEVELOPMENT. AN UPDATED SAFETY ANALYSIS REPORT WAS ISSUED IN 1984. THE FINAL SAFETY ANALYSIS REPORT, OR FSAR, WAS PUBLISHED IN LATE 1985 AS FABRICATION AND TESTING OF THE FLIGHT POWER GENERATORS WERE COMPLETED. THESE REPORTS, AND

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THE RESULTS OF THE SAFETY TEST PROGRAM, HAVE BEEN MADE AVAILABLE TO INSRP FOR USE IN DEVELOPMENT OF THEIR INDEPENDENT SAFETY EVALUATION. INSRP AND OTHERS IN THE SAFETY COMMUNITY, FURTHERMORE, HAVE PROVIDED CRITICAL REVIEW AT EACH STEP IN THE DEVELOPMENT OF THESE SAFETY REPORTS, AND THEIR COMMENTS HAVE BEEN INCORPORATED INTO THE FSAR.

THE ANALYSIS GENERAL ELECTRIC HAS CONDUCTED FOR THE FSAR IS BASED UPON POTENTIAL LAUNCH VEHICLE ABORTS, FAILURE PROBABILITIES AND ENVIRONMENTS DEFINED BY THE NASA. THIS INFORMATION IS PROVIDED IN A NASA-CONTROLLED DOCUMENT COMMONLY REFERRED TO AS THE "SHUTTLE DATA HANDBOOK". THESE POTENTIAL ABORTS, PROBABILITIES AND ENVIRONMENTS ARE DEFINED FOR SEVERAL PHASES OF THE LAUNCH PROCESS INCLUDING PRELAUNCH, FIRST STAGE ASCENT, SECOND STAGE ASCENT, ORBIT AND INSERTION. I HAVE ATTACHED A SUMMARY OF THESE MISSION PHASES AND ABORTS TO MY TESTIMONY AS FIGURE 4.3

THE SAFETY ANALYSIS, USING DIAGRAMS CALLED FAILURE ABORT SEQUENCE TREES (FASTS), TRACES EACH POTENTIAL ABORT THROUGH

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ALL THE ALTERNATIVES WHICH MIGHT LEAD TO A FUEL RELEASE. THESE DIAGRAMS CONSIDER ALL IDENTIFIED FAILURE MODES AND ARE VERY DETAILED. AN EXAMPLE OF SUCH A DIAGRAM FOR ONE SUCH EVENT IN THE PRELAUNCH MISSION PHASE IS ATTACHED TO MY TESTIMONY AS FIGURE 4. A TYPICAL SEQUENCE WOULD INCLUDE CALCULATIONS TO DETERMINE THE DEGREE OF HEAT SOURCE DAMAGE, AND CALCULATION OF THE TRAJECTORIES AND VELOCITIES OF HEAT SOURCE COMPONENTS SUBSEQUENT IMPACTS OF THESE HEAT SOURCE COMPONENTS UPON EXTERNAL STRUCTURES, RESIDUAL SHUTTLE FRAGMENTS OR GROUND SURFACES ARE ANALYZED AND ANY FUEL RELEASES PREDICTED. FOR CASES INVOLVING ORBITAL REENTRY, THE MOTION, TEMPERATURES, DEGREE OF ABLATION AND DAMAGE UPON GROUND IMPACT TO THE FUEL CONTAINMENT ARE PREDICTED. SAFETY TEST PROGRAM RESULTS ARE USED TO PREDICT FUEL RELEASES RESULTING FROM THE VARIOUS DAMAGE MECHANISMS.

THE RESULTS OF THE ABORT SEQUENCE ANALYSIS ARE EXPRESSED AS A LIST OF FUEL RELEASES, ASSOCIATED PROBABILITIES NAMED "SOURCE TERMS". EACH SOURCE TERM IS CHARACTERIZED BY MAGNITUDE, LOCATION AND PARTICLE SIZE OF THE FUEL RELEASE. VOLUME III

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OF THE FSAR, PREPARED BY NUS CORPORATION, REPORTS THE ULTIMATE DISPOSITION OF THESE POTENTIAL RELEASES IN THE ENVIRONMENT.

SOME OF THE POSSIBLE EVENTS EVALUATED CAN RESULT IN RELEASE OF FUEL. THE NUS' RISK ANALYSIS SHOWS EXTREMELY LOW PROBABILITIES OF DANGER TO HEALTH COMPARED TO EVERYDAY RISKS.

THANK YOU FOR GIVING ME THE OPPORTUNITY TO ADDRESS A VERY COMPLICATED SUJECT. I BELIEVE THAT A VERY COMPREHENSIVE ANALYSIS OF RTG SAFETY FOR THE GALILEO AND ULYSSES MISSIONS HAS BEEN ACCOMPLISHED AND I HOPE THAT MY PRESENTATION HAS BEEN HELPFUL. I BELIEVE THE RESULTS OBTAINED REPRESENT A CONSERVATIVE ASSESSMENT OF RTG SAFETY. THESE FACTS, ALONG WITH OUR UNBLEMISHED RECORD OF SUCCESSFUL AND SAFE LAUNCHES, PROVIDES CONFIDENCE FOR THE SUCCESS OF THE GALILEO AND ULYSSES MISSIONS.

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FIGURE 1

GPHS - RTG

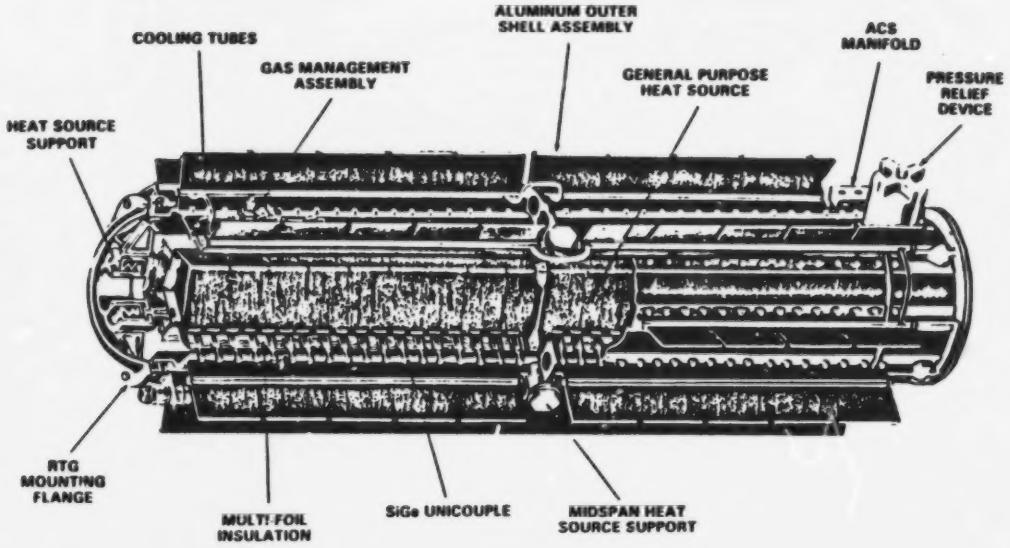

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FIGURE 2

GENERAL ELECTRIC

GENERAL PURPOSE HEAT SOURCE

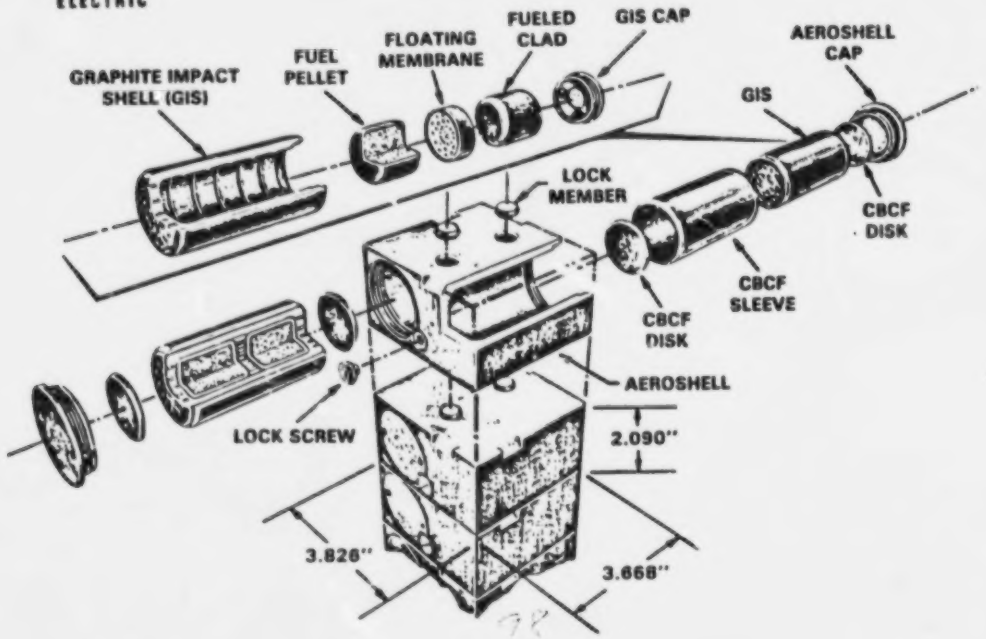
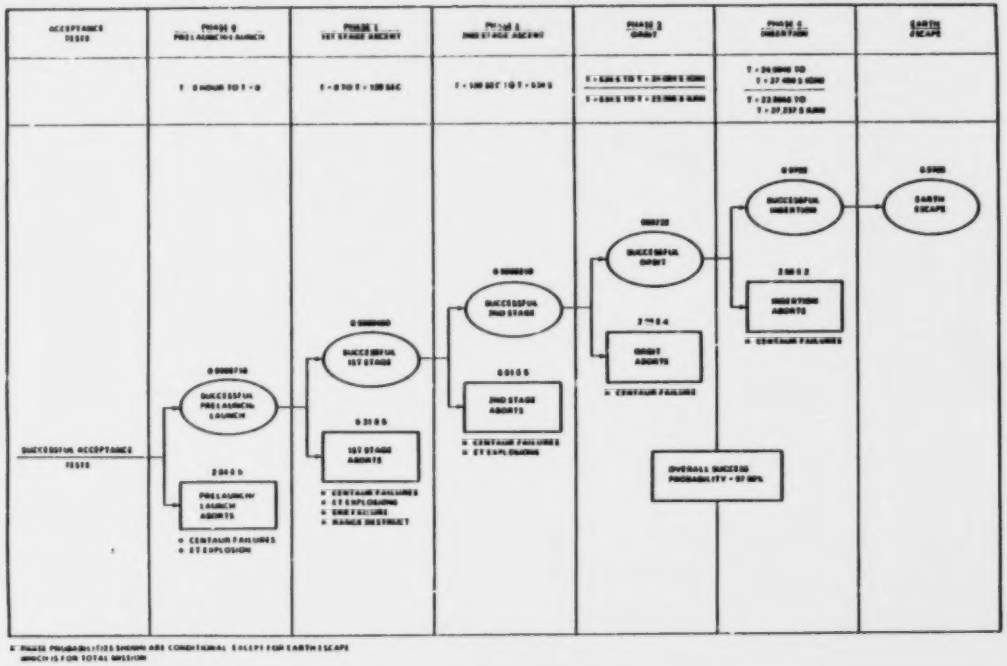


FIGURE 3



Mission Success and Abort Probabilities

FIGURE 4

TYPICAL FAILURE/ABORT SEQUENCE TREE (FAST)

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GILES C. SINKEWIZ

GILES C. SINKEWIZ IS GENERAL MANAGER OF SPACECRAFT OPERATIONS FOR GENERAL ELECTRIC'S SPACE SYSTEMS DIVISION, WHICH IS HEADQUARTERED IN KING OF PRUSSIA, PENNSYLVANIA. IN THAT CAPACITY, HE IS RESPONSIBLE FOR THE DESIGN AND CONSTRUCTION OF SATELLITE SYSTEMS FOR DEFENSE, SPACE SCIENCES AND TERRESTRIAL MISSIONS. AMONG THE MAJOR PROGRAMS HE MANAGES ARE THE LANDSAT SERIES OF EARTH RESOURCES SATELLITES FOR THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION; DIRECT TELEVISION BROADCAST SATELLITES FOR THE GOVERNMENT OF JAPAN; AND, THE DEFENSE SATELLITE COMMUNICATIONS SYSTEM, DSCS III, SATELLITES FOR THE DEPARTMENT OF DEFENSE. OTHER PROGRAMS INCLUDE THE GROUND MANAGEMENT SUPPORT OF THE LIFE SCIENCE EXPERIMENTS ON SHUTTLE FLIGHTS: DESIGN AND PRODUCTION OF THE GALLEY, WASTE COLLECTION SYSTEM, URINE MONITOR, VAPOR COMPRESSOR REFRIGERATOR FREEZER AND OXYGEN PARTIAL PRESSURE SENSORS FOR THE SHUTTLE CABIN AND REGULATED POWER SUBSYSTEMS FOR THE GLOBAL POSITIONING SATELLITE.

MR. SINKEWIZ WAS BORN ON MARCH 31, 1935 IN BELLEVILLE, ILLINOIS. HE RECEIVED AN M.S. DEGREE IN ELECTRICAL ENGINEERING FROM THE UNIVERSITY OF MISSOURI IN 1960. HE HAS BEEN A SYSTEMS PROJECT ENGINEER FOR RCA, AN INSTRUCTOR IN THE ELECTRICAL ENGINEERING DEPARTMENT OF THE UNIVERSITY OF MISSOURI, AND VICE PRESIDENT OF PROGRAMS FOR HARRIS CORPORATION. HE JOINED GENERAL ELECTRIC COMPANY'S SPACE SYSTEMS DIVISION AS GENERAL MANAGER OF THE TECHNICAL SUPPORT DEPARTMENT IN 1981 AND WAS NAMED GENERAL MANAGER OF SPACECRAFT OPERATIONS IN 1983.

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Mrs. LLOYD. Thank you Mr. Sinkewiz.

Mr. Vogelberger, would you go ahead, please.

Mr. VOGELBERGER. Madam and Mr. Chairman, and members of the subcommittees, I appreciate the invitation and opportunity to share with you our views and experience relating to the utilization of RTG's for space missions. The history of space RTG missions has been an impressive success story, and it has certainly been more eloquently described here today already than I had planned to do or could do.

My company, Teledyne Energy Systems, has been a major developer of RTG's for these space missions since 1959. We developed, qualified and produced the flight hardware for 11 of the spacecraft launched up through 1975. Our SNAP-19 RTG's continue to provide electrical power to Pioneer 10, which was the first man-made object to leave our solar system in May of 1985 and Pioneer 11, which was the spacecraft to fly by Saturn in 1979.

A pair of SNAP-19 RTG's was used on each of the two Viking landers which have already been mentioned previously by Congressman Nelson. In all if these space RTG hardware development programs, we had a systems engineering responsibility which included reliability and nuclear safety studies and the preparation of the safety analysis report for the missions.

As a result, we have developed a body of expertise and experience in the methodology and assessment of nuclear safety. For later missions such as the Department of Defense LES 8 and 9 missions and NASA's Voyager I and II missions, we were not the prime hardware development contractor. We were asked to contribute our expertise by providing safety support services to the U.S. Air Force to help them in their responsibility as a member of the Interagency Nuclear Safety Review Panel. In the early stages of the Galileo RTG development program, we were a prime contractor developing a new thermoelectric converter technology for the mission.

In 1979, after it was decided to use the proven Voyager thermoelectric technology for Galileo and Ulysses, Teledyne Energy Systems was no longer the prime RTG contractor/developer, and we were then again asked by the Air Force to furnish technical support services for their use in assessing the nuclear safety of the missions. One of the support tasks which we conducted in 1982 and 1983 was a reliability review. Our report on that task was prepared by a highly qualified and recognized subcontractor, Sierra Energy & Risk Assessment Inc. of Sacramento, CA, whose principal investigator and the report author, Bob Weatherwax, had previously done similar studies for the Air Force and in the nuclear powerplant field.

His report was approved and submitted by Teledyne Energy Systems and later issued as an Air Force report entitled, "Review of Shuttle Centaur Failure Probability Estimates for Space Nuclear Missions Applications." It was basically a review of vehicle malfunction and response mode studies and reliability data which had been done by another contractor for NASA, and the author concluded that a more comprehensive reliability approach should be used to define and analyze accident scenarios for shuttle Centaur launches of nuclear missions.

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In reaching his conclusions and making recommendations for further risk assessment analyses in the ongoing Galileo safety analysis, Mr. Weatherwax presented sample calculations and risk assessment rationale to demonstrate his views. And it was some of these examples which have been referred to in the press following the *Challenger* disaster, as suggesting higher probabilities of solid rocket booster motor failure and catastrophic shuttle accidents. I have with me today Mr. Denton Anderson, who is our program manager and our principle scientist for those Air Force technical support tasks.

He reviewed and approved the Weatherwax report for submission to the Air Force and he will try to answer any specific questions you may have on the context and content of that report. I would also comment that subsequent to the technical support task for the Air Force, Mr. Andersen was also asked to contribute and did to the formulation of the Department of Energy General Electric Safety Test Program for the ongoing Ulysses/Galileo safety analysis report.

Several earlier witnesses and subcommittee members have mentioned 19 successful RTG's space missions out of 22 launches. There has also been mention of the three launch aborts, so I won't go into those, although they are in my written testimony. As far as our viewpoint is concerned, these three mission failures out of the 22, at least partially validated by the actual event occurrences, the safety and design analyses of those missions.

The early mission aborts added data and perspective to the developing body of aerospace nuclear design and safety assessment knowledge as will the unfortunate 51-L shuttle abort. I agree with Mr. Sinkewiz and others before me that the Nation's 25 years of experience with using RTG's on space missions has a successful record of performance and safety. We are confident that this experience and the resulting accumulation of technical and organization review knowledge and procedures which are in place, can and will insure that future missions such as Galileo and Ulysses can be launched with minimal risk and high probability of success.

Thank you for your invitation to state our views, and we will be happy to try to answer any questions.

[The prepared statement of Mr. Vogelberger follows:]

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STATEMENT OF
PETER J. VOGELBERGER, JR.
PRESIDENT, TELEDYNE ENERGY SYSTEMS

BEFORE THE
U. S. HOUSE OF REPRESENTATIVES
COMMITTEE ON SCIENCE AND TECHNOLOGY
SUBCOMMITTEES ON ENERGY RESEARCH AND PRODUCTION
AND SPACE SCIENCE AND APPLICATIONS

MARCH 4, 1986

Madam and Mr. Chairmen and Members of the Subcommittees, I appreciate the invitation and opportunity to share with you our views and experience relating to the utilization of radioisotope-fueled thermoelectric generators for space missions. The history of space RTG missions has been an impressive success story. Many of the missions on which RTG's were used could not have been done at all or nearly as well without their use. As I commented to you last fall, there have been a total of 34 RTG's launched on 19 successful space missions, including both earth orbital and outer planet spacecraft. My company, Teledyne Energy Systems, has been a major developer of RTG's for these space missions since 1959. We developed, qualified, and produced the flight hardware for 11 spacecraft launched up through 1975. These included the original SNAP 3A RTG's on Transit navigational satellites in 1961 as a component of a hybrid solar/nuclear-powered system. Our SNAP 9A's were launched on three more Transit satellites in 1963. Two SNAP 19's were then launched on each of two NASA Nimbus weather satellites in 1968 and 1969. Four generators, improved versions of the same SNAP 19, were launched on each of NASA's Pioneer 10

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and 11 outer planet missions in 1972 and 1973. These units continue to provide electrical power to Pioneer 10, which was the first man-made object to leave our solar system in May 1985, and Pioneer 11, which was the first spacecraft to fly by Saturn in 1979. A pair of SNAP 19 RTG's was used on each of the two Viking Landers which were launched in 1975 and landed on Mars in 1976 to search for life on Mars and study the geology and meteorology of that planet. The Viking RTG's provided both electrical power and heat for the instrument bay.

In all of these space RTG hardware development programs we had a systems engineering responsibility which included reliability and nuclear safety studies and the preparation of the safety analysis report for the missions. In some of the early missions we also had a responsibility for fuel capsule and reentry protection design and development. As a result, we have developed a body of experience and expertise in the methodology and assessment of nuclear safety. For later missions, such as the Department of Defense Lincoln Experimental Satellite 8 and 9 and NASA's Voyager 1 and 2 missions, where we were not the RTG development contractor, we were asked to contribute our expertise by providing safety support services to the U. S. Air Force to help them in their responsibility as a member of the Inter-Agency Nuclear Safety Review Panel. In the early stages of the Galileo RTG development program, we were a prime contractor developing a new thermoelectric converter technology for the mission. In 1979, after it was decided to use the proven Voyager type thermo-

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electric technology for Galileo and Ulysses, Teledyne Energy Systems was no longer the prime RTG contractor/developer and we were then asked again by the Air Force to furnish technical support services for their use in assessing the nuclear safety of the missions. One of the support tasks we conducted in 1982 and 1983 was a reliability review. Our report on that task was prepared by a highly qualified and recognized subcontractor, Sierra Energy and Risk Assessment, Inc., of Sacramento, California, whose principal investigator and the report author, Bob Weatherwax, had previously done similar studies for the Air Force and in the nuclear power plant field. His report was approved and submitted by Teledyne Energy Systems and later issued as an Air Force report entitled "Review of Shuttle/Centaur Failure Probability Estimates for Space Nuclear Mission Applications." It was basically a review of vehicle malfunction and response mode studies and reliability data which had been done by another contractor for NASA and the author concluded that a more comprehensive reliability approach should be used to define and analyze accident scenarios for Shuttle/Centaur launches of nuclear missions. In reaching his conclusions and making recommendations for further risk assessment analyses in the on-going safety analysis for Galileo, Weatherwax presented sample calculations and risk assessment rationale to demonstrate his views and it was some of these examples which have been referred to in the press following the Challenger disaster as suggesting higher probabilities of solid rocket booster motor failure and

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catastrophic Shuttle accidents. I have with me today Mr. Denton Anderson, who was our Program Manager and Principal Scientist for the Air Force technical support tasks. He reviewed and approved the Weatherwax report for submission to the Air Force and will try to answer any specific questions you may have on the context and content of that report. I would also comment that, subsequent to the technical support tasks for the Air Force, Mr. Anderson was also asked to contribute, and did, to the formulation of the DOE/General Electric Company safety test program for the on-going Galileo/Ulysses safety analysis report. Teledyne Energy Systems during the past 10 years has continued to conduct reliability and nuclear safety assessments in order to prepare safety analysis reports for terrestrial Plutonium-238 and Strontium-90 fueled RTG missions, some of which have made use of all or part of the designs and hardware from the space RTG plutonium heat sources.

Earlier I mentioned 19 successful RTG space missions. There were actually 22 launches. In the first 10 years of space RTG utilization, there were three mission aborts out of nine attempts. However, in the last 15 years there have been 13 missions with no failures. In the case of the three early mission aborts, the design and safety analyses of the RTG's and accident scenarios were at least partially validated by actual event occurrences. In 1963 one of the Transit SNAP 9A satellites did not achieve orbit and the plutonium heat source was burned up

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during reentry into the upper atmosphere as it had been designed to do. Later RTG heat sources have been designed for intact reentry and impact rather than atmospheric burnup and dispersion. In 1968 NASA's Nimbus 3 launched from Vandenberg was destroyed shortly after launch by the Range Safety Officer and the RTG's with their Plutonium-238 fueled capsules were recovered intact from the Santa Barbara Channel. In 1970, when Apollo 13 had system problems which prevented its landing on the Moon, the SNAP 27 RTG was ditched along with the Lunar Exploration Module in the Western Pacific, and the plutonium heat source reportedly still rests safely as designed at the bottom of the deepest part of the ocean. These early mission aborts added data and perspective to the developing body of aerospace nuclear design and safety assessment knowledge as will the unfortunate L-51 Shuttle abort.

The nation's 25 years of experience with using RTG's on space missions has a record of successful performance and safety. We are confident that this experience and the resulting accumulation of technical and organizational review knowledge and procedures, which are in place, can and will ensure that future missions such as Galileo and Ulysses can be launched with minimum risk and high probability of success.

Thank you for your invitation to state our views. We will be happy to try to answer any questions.

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Mrs. LLOYD. Thank you very much, Mr. Vogelberger.

Mr. Sinkewiz, I understand that in December 1985 that General Electric, in a letter to the Department of Energy, reevaluated the effect on the source term expectation by increasing the SRB failure probabilities by two orders of magnitude; is that not correct?

Mr. SINKEWIZ. I think that's roughly correct. I do not remember the exact number.

Mrs. LLOYD. But the increase didn't change the expectations greatly. Now, if the radiological releases are not significantly altered by such an increase in failures to the SRB, would you explain this to the committee?

Mr. SINKEWIZ. Yes, ma'am, I will attempt to.

Mrs. LLOYD. That is a big order, especially at a quarter to 5.

Mr. SINKEWIZ. Or any time of the day.

That one particular source term was changed as a result of doing a reevaluation based on information we were given for a different probability of failure for the SRB. That did not change significantly the overall result because that term is one term of many terms in an equation that when summed together and divided by the probability of the accident occurring was one term in a series of terms that overall when added together did not have a large effect—in fact, it had a relatively insignificant effect on the whole result. That one term did change significantly.

Mrs. LLOYD. But it didn't change the probability of failure.

Mr. SINKEWIZ. Because, again, that was only one term of many terms in the analysis for a failure that had many possibilities——

Mrs. LLOYD. That was just one factor of many.

Mr. SINKEWIZ. One factor, yes.

Mrs. LLOYD. Well, the next one is a really dandy question, but they are questions that we do need to get on the record. I hope you will bear with us.

The probabilities assigned to the various shuttle failure modes and their relevance to the RTG system within the shuttle orbiter leads to the calculation of the radiological source terms. Would you describe for the committee the significance of the source term values and what they really mean and the potential effect on individuals? How do you understand the significance is what I am really trying to get at.

Mr. SINKEWIZ. Yes, I think I do understand the question.

Mrs. LLOYD. The path of an accident occurring, which is our source term, on the release of the fuel which would pose a health hazard.

Mr. SINKEWIZ. I almost have to come back to what I had just said, and that is that the significance is that any source term that we derive from a particular scenario of an accident that would lead to some kind of fuel release, which of course is a definition of a source term, may be one of several different source terms in a particular accident scenario such as, for example, with the Centaur and in the shuttle on the launch pad.

Mrs. LLOYD. Plutonium in the RTG is our source of concern.

Mr. SINKEWIZ. But the accident scenario starts with a particular failure mechanism within either the shuttle system or the Centaur, and that analysis is traced through to what kind of mechanisms could result in fuel release, and the fuel release is in fact a critical

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issue and a question, and any one of several things such as an overpressure, as has been described here today, or flat plate impinging upon the RTG or the RTG striking an object, then the shuttle could result in some fuel release, and what we have done in our analysis is take a look at all the different possible mechanisms that could result in fuel release, which we again call source terms, into sum of those divided by the probability of the accident is in fact the term that we get as a result of the—not the probability, but the accident occurring.

Mrs. LLOYD. How do you get from the accident condition to the place where you can actually understand whether or not this accident would cause the RTG to fracture and release this radioactive material?

Mr. SINKEWIZ. We have taken——

Mrs. LLOYD. What are the steps?

Mr. SINKEWIZ. OK, the steps are that we have taken the different sequences. As I indicated before, the on pad, the first stage ascent and so on, and we looked at approximately 20 different accident scenarios, and we took a typical scenario and said, OK, would that scenario, for example, result in the graphite casing around the clad around the fuel to be penetrated. And you get either a yes or no from that, and if you get a yes, then you proceed down the analysis to determine will the clad be penetrated and fuel released for different conditions such as, again, hitting an object, or an object hitting it.

Then you take the other side of that tree and work down, and if the graphite is not penetrated, but it does strike an object, will it in fact break open and fuel released. We go down a sequential tree of analysis, and I did put in my testimony for the record one such tree, and there are 20 of those.

Mrs. LLOYD. Thank you. Mr. Morrison.

Mr. MORRISON. First, just a comment that I think both of the firms you represent have excellent records, and we are delighted with the involvement in a range of programs, particularly this one. Just a general question, do you feel in your laboratories, when you are doing your own research and development work that you have easy access to the folks at NASA, within the Department of Energy, anyone you may need to talk to when you have got a better idea, as your scientists work with such machines as RTG's.

Mr. SINKEWIZ. We certainly feel that we do have easy access, yes.

Mr. MORRISON. Have you proceeded with unsolicited proposals for change or for modification?

Mr. SINKEWIZ. We have had some changes, but not an inordinate number of changes to this program or any others for that matter. So, no, we have not had a large number of unsolicited proposals.

Mr. MORRISON. Maybe a question to both of you, the RTG's that you have built that have been so successful, were these your own designs, or were these produced, say, from work done at a national laboratory. We will be hearing from them next. What is the mechanism here that has been so effective?

Mr. VOGELBERGER. I think it is a little bit of all of those things. What has occurred has been an iterative process over the years with my company working for and with the AEC, and then the Department of Energy, and rigorously competing against General

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Electric. We have been competitors over almost the whole history of this thing that has been talked about today.

All of that process has been an improvement process as resulted in the kinds of improvements that you are referring to. I think that on the subject of being able to talk to the agencies, not only the Department of Energy who is the development agency for RTG's, but to the users—to NASA and the Air Force, has certainly been very open. We have never had any difficulty with that, and I don't think, as Giles said, GE has either, and we are certainly not bashful about submitting unsolicited proposals, and we do in fact do that.

We don't get too many of them, but we certainly submit them.

Mr. MORRISON. Thank you. Just off the top of my head, one of the things that I am sure will be considered as we look at the *Challenger* accident, and it was some escape mechanism potential as we had in many of our military aircraft. Could we build an RTG that in fact had its own separate launch system that would remove it from a potential accident scene?

Mr. VOGELBERGER. I think we certainly could do that, the question is, can it react fast enough. You saw the television pictures of what occurred and the question is what kind of response time is necessary, and I certainly can't answer whether that's possible. I imagine that the NASA launch people can answer that question a lot better than an RTG maker can.

Mr. MORRISON. It has to be a little frustrating for you because you have built a very good machine, and in essence, the only time you get into trouble is when somebody else's machine fails.

Mr. VOGELBERGER. So far that has been the case.

Mr. MORRISON. Let's hope the odds continue to be with you.

Thank you, Madam Chairwoman.

Mrs. LLOYD. Thank you. Mr. Nelson.

Mr. NELSON. Mr. Sinkewiz.

Mr. SINKEWIZ. Yes, sir.

Mr. NELSON. Is there anything that you think could be done to make the RTG safer?

Mr. SINKEWIZ. There are changes that can be implemented to make the RTG's safer. One could structurely improve the structural integrity, making the aluminum walls, the casing around the RTG's thicker. One could invision actually putting a very sturdy and strong cage around them. There is weight and issues associated with that, and there is also the issue of what kind of change does that really make to the overall safety process, and I think that is what really has to be evaluated, and that evaluation made in terms of what additional safety factors do you accomplish for the additional weight that you have to carry.

Mr. NELSON. Given the Department of Energy gentlemen, Dr. Wilcox, had testified that he thought that the probability of an explosion on the pad where it would hit the steel of the launch tower was some extraordinary probability—1 in 10 million. Given that very low probability that that would occur, what would you as the designer of this system do any different that would keep it from breaking apart if that did occur on the pad?

Mr. SINKEWIZ. Given that it is a low probability——

Mr. NELSON. 1 in 10 million.

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Mr. SINKEWIZ. I don't believe that there is anything as a designer of the RTG that I would do differently than I am currently doing.

Mr. NELSON. Do you agree with Dr. Wicox's testimony that if that occurrence, 1 in 10 million did occur, that you could then clean it up there on the pad in a fairly contained fashion?

Mr. SINKEWIZ. We have not, as a company or an individual looked at that question per se, so I cannot really render an opinion on that.

Mr. NELSON. Mr. Vogelberger, do you have an opinion on that?

Mr. VOGELBERGER. I think it is probably true, and we haven't made any studies of that either, that what is on the pad can be cleaned up. The question is how much of what is released is not on the pad, what might have been vaporized or blasted off in the meteorology in the other factors of the explosion situation.

Mr. NELSON. Let me ask you, Mr. Vogelberger, about—let me go back to the report. This thing is getting dog-eared.

Mr. VOGELBERGER. If I may, I would like to have Mr. Anderson join me at the table here in case I can't answer the question.

Mr. NELSON. Now, if I recall in here, you all would agree with the statements that were said today about that when you are trying to assess numerical probability that your point at which you look at it is the potential failure of the SRB's; is that correct, SRB's, solid rocket boosters. Is that correct?

Mr. VOGELBERGER. I think it is fair to say that we agree that the solid rocket booster is the highest probability of failure, if that is your question.

Mr. NELSON. OK, now, and that is what other witnesses have said here today. All right, given that fact, if I recall in your statement or in this Teledyne report, you said that the probability of their being a failure with the SRB's was 1 in 70; is that correct?

Mr. VOGELBERGER. That is one of several different numbers that is in that report, yes, sir.

Mr. NELSON. You mean there are other numbers——

Mr. VOGELBERGER. There is range of numbers in there, and that happens to be one within the range.

Mr. NELSON. Well, what are the ranges of the other numbers then?

Mr. VOGELBERGER. I am going to ask Mr. Anderson to respond.

Mr. NELSON. Sure.

Mr. ANDERSON. That was the mean of the range, and I think the actual range extended from about 3 in 1,000 to approximately 3 in 100, if I recall.

Mr. NELSON. 3 in 1,000 to 3 in 100?

Mr. ANDERSON. Yes.

Mr. VOGELBERGER. That is the same thing as saying 1 in 33 to 1 in 1,000—correction, 1 in 300; 1 in 33 to 1 in 300.

Mr. NELSON. OK, so you took the mean there, and that is 1 in 70. OK, now you have heard the testimony today, and nobody agrees with that. To the contrary, the group from the Interagency Nuclear Safety Review Panel, you have heard just say that they felt like the probabilities were 1 in 1,000. Why the difference?

Mr. VOGELBERGER. I am going to answer and then let Denton comment. I think what the INSRP people said was that when you squeezed a number out of them, it was 1 in 1,000. However, they

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have felt that the normal kinds of degrees of uncertainty on such a number were two orders of magnitude, and they quoted the 10 to the minus 4 number or 1 in 10,000 in the other study, and our number, which is essentially 1 in 100, which you call 1 in 70, as being within those limits, and therefore essentially no real difference between the two studies and their answer.

Mr. NELSON. You know, somebody could go just stark raving mad up here listening to all of these numerical probabilities. Well, I want you to answer some more, because I am not sure I understand your answer.

I heard NASA say 1 in 100,000. Then I heard one of those other reports—Wiggins—say 1 in 10,000, and I heard the Interagency Nuclear Safety Review Panel say 1 in 1,000, and I hear you saying 1 in 100, not in 1 in 70. You just said it is 1 in 100. Tell me. Elucidate me.

Mr. ANDERSON. The estimate that is in the report, the range and the mean, were based on the historical data collected. The difference between results shown on the report and that in the Wiggins report—those results in the Wiggins report, largely due to factors of reduction that were applied by Wiggins, a factor of 10 or 100, and so they quoted probabilities of 10 to the minus 3 or 10 to the minus 4. But in the original report, a number was referred to like 1 in 57 was the average probability historically.

I do agree with Dr. Silveira that the characteristics, the way this particular solid rocket booster was designed is different from the designs of the historical cases which had these failures, and one has to take that into account.

Mr. NELSON. Was that taken into account in your report?

Mr. ANDERSON. No.

Mr. NELSON. It was not.

Mr. ANDERSON. No.

Mr. NELSON. The fact that the SRB's are man-rated as opposed to what you were looking at as unmanned.

Mr. ANDERSON. Correct.

Mr. NELSON. Unmanned-rated; is that correct? So that is a difference.

OK, now let me ask you about that. You talked about historical data upon which you base your conclusions, but then I heard one of the witnesses today say that the historical data is that they have never had a failure of an SRB on the unmanned or less safe systems, so how do you draw a conclusion that it is 1 in 100 from a historical data that has never had a failure on the Titan 2-C's and the Titan 34-D's.

Mr. ANDERSON. It really depends on how much emphasis you put on the Titan data versus all of the collective data. There were 1,903 trials in total, all of the motors that were looked at by Wiggins.

Mr. NELSON. SRB's—solid rockets.

Mr. ANDERSON. Solid motors, yes.

Mr. NELSON. Solid motors.

Mr. ANDERSEN. Right.

Mr. NELSON. 1,900 of them. Were some of those tests?

Mr. ANDERSON. Some were tests, I believe. I am really not fully aware of all the data and all of the failure characteristics. That in-

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formation, I believe, is considered sensitive, and was not supplied us.

Mr. VOGELBERGER. I think it is true to say that it goes back to the some of the early Polaris launches through all of the solid rocket launches since that time, since there was any data.

Mr. NELSON. Thank you for clarifying your data based on the non-man-rated system. Now was there a factor that you either did or did not consider? Please enlighten me with regard to the effect of the learning curve that we have had as we have utilized solid rocket motors as to something that we learned that we should have changed, and then we changed it or corrected it, which made the system the probability—the statistical probabilities would have been more favorable, more safe.

Is that something you considered?

Mr. ANDERSON. We did not consider it because we did not have the information to use. In other words, if there were an earlier failure, what was done about that and how was that factored into the design of the present system, I don't know the answer to that.

Mr. NELSON. I see. Go ahead.

Mr. VOGELBERGER. Wiggins apparently didn't either.

Mr. NELSON. All right, well I don't care what Wiggins—you know, what I am trying to do is get us up to date so as to whether or not some of my friends are going to climb in an orbiter with an RTG and a Centaur in it. So given the fact of that kind of focus, that was another factor that you did not use in coming to your conclusion, the learning factor of updating yourself on things that you had learned.

Mr. ANDERSON. That's true.

Mr. NELSON. As far as safety of—reliability, that is, of SRB's. So the up-to-date, the Congress, in exercising our oversight role here of NASA and other agencies, then you would say that there are additional points of data that would update your figure of your statistical reliability.

Mr. ANDERSON. I would assume that to be the case. I am not aware of that myself.

Mr. NELSON. Thank you for this additional information.

Do you want to make any comments of—here I go to the reports again. The Sandia made some comments about your particular report. Do you want to make any comments about Sandia's?

Mr. VOGELBERGER. We haven't really seen it.

Mr. ANDERSON. I'm sorry to say we haven't it.

Mr. VOGELBERGER. We have not seen that report, nor have we seen the comments other than a few things that were mentioned here today.

Mr. NELSON. It was printed in December 1984. Nobody has had the courtesy to send you a copy?

Mr. VOGELBERGER. Correct.

Mr. NELSON. And you don't have access to it? Has it been classified?

Mr. VOGELBERGER. We haven't seen it.

Mr. ANDERSON. I wasn't really aware that it was issued.

Mr. NELSON. December 1984, that is almost a year and a half ago. Well, why don't I give you my copy, and would you look at it, and at your convenience would you respond if you have any addi-

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tional comments on their critique of your report? This is a critique of your report and the Wiggins report.

Would you do that for us?

Mr. VOGELBERGER. Yes, sir.

Mr. ANDERSON. Yes, sir.

Mr. NELSON. I appreciate it. Thank you, Madam Chairman.

Mrs. LLOYD. Thank you very much, Mr. Nelson. Thank you, gentlemen, for being before these committees today, and we will be submitting questions in writing to you, but in the interest of time, I think we will call it quits for now with you. Thank you.

Our next panel includes Dr. Roy Zocker, who is the leader of the Physical Metallurgy Group in the Materials Science Division of Los Alamos National Laboratory; Dr. David Carlson is Supervisor at Light Water Reactor Safety Technology Division at Sandia National Laboratories; and Mr. John Casani, who is Project Manager of Galileo, Project Jet Propulsion Laboratory.

We welcome you to our hearings this evening, I think it is right now. Dr. Zocker, we look forward to your testimony. Please proceed.

STATEMENTS OF DR. ROY W. ZOCKER, LEADER OF PHYSICAL METALLURGY GROUP, MATERIALS SCIENCE DIVISION, LOS ALAMOS NATIONAL LABORATORY; DR. DAVID D. CARLSON, SUPERVISOR, LIGHT WATER REACTOR SAFETY TECHNOLOGY DIVISION, SANDIA NATIONAL LABORATORIES; AND JOHN R. CASANI, PROJECT GALILEO MANAGER, JET PROPULSION LABORATORY

Dr. ZOCKER. I would like, first of all, to read the statement that delineates, really, what we do and what we have done in relation to these RTG's.

Madam Chairwoman, thank you for opportunity to discuss the role of the Los Alamos National Laboratory in the Department of Energy's Radioisotope Power Program. I would like to make a brief statement and then respond to any questions you or the members of your subcommittee may have.

The Los Alamos National Laboratory has participated in space radioisotope power programs since the late 1960's. During that time we have worked on the technology, the safety testing and the safety analysis of $^{238}PuO_2$ heat sources used in the Pioneer mission to Jupiter and Saturn; the Viking mission to the surface of Mars; the Transit navigational satellite; the LES 8/9 communications satellite; the Voyager mission to Jupiter, Saturn and Uranus; and most recently the scheduled Galileo mission to Jupiter and the European Space Agency's Ulysses solar polar mission.

Los Alamos has developed many unique capabilities and facilities for testing $^{238}PuO_2$ radioisotope heat sources to determine how they are affected by exposure to the thermal and mechanical environments that might be present during an accident. Many of the safety tests can be performed on the actual $^{238}PuO_2$ fueled heat sources, while others must be performed on samples in which a simulant is substituted for the radioisotope fuel. The accident conditions of concern include fires, explosions, fragment impacts, reentry to the Earth's atmosphere and Earth impacts that might

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result during a launch phase malfunction. We have also run tests to determine what would happen to heat sources if they were deposited in aquatic or terrestrial environments.

Test conditions imposed on the samples are based on the user agency's definition of accident environments which are transmitted to Los Alamos via the DOE. There is no single, unique environment. Instead there is a range of environments that depend on the details of the accident. For instance, explosions can be of many intensities, fragments can be of many sizes and velocities, and impact targets can range from water or soft dirt to harder materials like granite or steel.

As much as possible, the test conditions we use span the ranges as they are presented in the definition of environments. In addition to the actual safety tests for specific systems, we perform many research and development activities to characterize the heat source components and their chemical and physical interactions with each other and with their surroundings.

Our contributions to the development of radioisotope power sources and radioisotope heaters for the scheduled Galileo and Ulysses missions have been in several areas. One item that hasn't been mentioned is the fact that there are heater units aboard these spacecraft that are also radioisotope powered and simply are heaters.

Starting in 1978 we designed, tested and fabricated, and delivered small light-weight radioisotope heater units that will provide local heat to instruments on the Galileo Orbiter and Probe. Because of our lead role in the development of this heat source, we did not perform final safety analyses. Other DOE agencies were assigned the responsibility of performing final safety analysis to ensure broad safety oversight. In support of these activities, we performed the required safety-related tests and presented the results of those tests as formal reports to both formal and independent review communities.

In 1976, we undertook the development of a prototypical $^{238}PuO_2$ general purpose heat source. The design was delivered to DOE and its production agencies at the end of 1979. This design was further refined by DOE and is the basis of the General Purpose Heat Source, GPHS, which provides the thermal energy for the RPHS thermoelectric generator, which will provide electrical power for the Galileo and Ulysses missions.

For the past 6 years Los Alamos has been conducting extensive safety testing on the GPHS in both its pre-production and its production forms. Again, because of our lead role in the development of the prototype heat source, we did not perform a final safety analyses. Other DOE agencies performed the final safety analyses to ensure broad safety oversight.

Los Alamos National Laboratory has a commitment to the protection of the public health and safety and of the environment as an integral part of all of its research and development activities. In looking toward the future, we will continue to apply our unique capabilities and experience in technology development, safety testing, and safety analyses of $^{238}PuO_2$ heat sources in the support of national programs which require isotope power sources for space and terrestrial applications.

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Madam Chairwoman, this concludes my statement. I would be pleased to respond to any questions the subcommittee may have.

Mrs. LLOYD. Thank you, Dr. Zocker. Dr. Carlson.

Dr. CARLSON. Thank you. Accompanying me today is Dr. Ronald Iman, statistician for our analysis; he is here to help address any questions you may have.

Mrs. LLOYD. Fine.

Dr. CARLSON. I have provided you my full testimony. I would like to summarize it at this time.

In the spring of 1984, the Air Force Weapons Laboratory requested that Sandia provide an independent review of issues raised concerning the range safety hazards associated with the missions involving RTG's scheduled for launch aboard the space shuttle in May 1986. In this testimony I will describe the issues raised and the conduct and conclusions of our independent assessment.

The objectives of our work were to independently review the work of the J.H. Wiggins Co. and Sierra Energy & Risk Assessment Inc., subcontractor to Teledyne, to identify the major differences between the vehicle failure probability estimates; to develop an informed opinion of the merits of each work; to evaluate the potential importance of various issues; and to formulate an independent opinion of vehicle failure probabilities if possible.

The work was conducted over a 2-month period. Resources did not permit a full independent review of the original range safety hazard analysis to identify additional issues, nor did they permit an independent calculation of vehicle response probabilities. Rather our work consisted primarily of a review of the issues raised in the SERA report. Sierra Energy & Risk Assessment concluded that vehicle failure probabilities, as estimated by Wiggins, are substantially low, perhaps by up to a factor of 1,000 in some instances.

This was attributed to a number of issues, including the estimate of the failure probability of the solid rocket boosters, the techniques used for calculating the probabilities of other modes of vehicle failure, and limitations and omissions from Wiggins analysis. Both Wiggins and SERA identified solid rocket booster failure as the dominant failure mode to the mission.

Both reports discussed the treatment of solid rocket booster failure data in considerable depth. The failure rate was estimated from experience with earlier solid rocket boosters. Wiggins and SERA's estimates differed by more than a factor of 10. Central to the discussion was whether and how to incorporate learning into the analysis; that is, whether and how the failure rate has decreased as more experience with various types of solid rocket boosters has been obtained.

Wiggins argued that the present solid rocket booster failure rates are less than historical data would indicate. This was based on the judgment that solid rocket technology has improved over time. The report, however, provided no analytic justification for this judgment. SERA evaluated the historical data, but their approach would bias the failure rate estimate upward if technology has in fact improved over time.

Our review of the data suggests that learning may be important to the failure estimate. We developed a statistical approach that in-

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corporates learning, if it exists, into the failure rate estimate. However, in the absence of more specific information regarding failures of various historical rocket systems, we were unable to develop an independent estimate of solid rocket booster failure.

SERA raised a number of issues regarding the techniques for estimating the probabilities of other modes of vehicle failure. Our review suggests that several of SERA's criticisms are valid. However, their claim that the estimates of vehicle failure were several orders of magnitude too low was not supported by our review. Our analysis show that of the methodological issues raised, only two were likely to substantially influence the failure probability estimates.

The first was SERA's view that there exists considerably more uncertainty in the component failure rates than Wiggins assumed. However, our review concluded that there was not an adequate basis in the SERA report for their view. Second, SERA argued that failure rate multipliers should be used to account for environmental influences on failure rates. We concluded that there was precedent for use of failure rate multipliers in other safety-related studies that provide input to the mission safety analysis.

Several other issues were examined, but they appeared to have only modest impacts on the results. Although, we did not develop an alternative estimate of vehicle response mode failure probabilities, we found no reason to believe that a reevaluation considering these issues, would increase the estimate of failure probability by a factor of 1,000.

In summary Sandia's review identified some technical deficiencies in some areas in which more justification would improve the Wiggins reports, credibility and traceability. SERA identified several shortcomings in Wiggins reports, not all of which were previously acknowledged by Wiggins, but several of which were apparently were outside their scope of work.

On the other hand, we do not believe that SERA adequately supported their conclusion that current probability estimates could be low by several orders of magnitude. Neither Wiggins nor SERA convincingly estimate the probability of the dominant failure mode solid rocket booster failure. We presented an improved statistical approach to estimating this failure rate. Although the possibility of significant error in Wiggins estimate of vehicle probability remains, our evaluation of methodological issues provided no evidence of such large underestimates.

Thank you very much. Ron and I would be glad to answer any questions you may have.

[The prepared statement of Dr. Carlson follows:]

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Testimony of David D. Carlson
delivered to the
Energy Research and Production and
Space Science and Applications Subcommittees
U.S. House of Representatives
Review of Radioisotopic Thermal Generators for Space Missions

March 4, 1986

I am David D. Carlson, Supervisor of the Light Water Reactor Safety Technology Division at Sandia National Laboratories. In the spring of 1984, the Air Force Weapons Laboratory requested that Sandia provide an independent review of issues raised concerning the range safety hazards associated with the Galileo and International Solar Polar missions scheduled for launch aboard the space shuttle in May 1986. Both spacecraft for these missions employ radioisotopic thermal generators (RTGs) for electrical power. In this testimony, I will describe the issues raised and the conduct and conclusions of our independent assessment.[1]

As part of the development of information for evaluating the risk from shuttle missions, the National Aeronautics and Space Administration contracted with the J. H. Wiggins Company to evaluate the likelihood of shuttle/Centaur vehicle failure and to assess the range safety hazards associated with such a failure.

The Wiggins' reports[2,3,4] focus on vehicle failure probabilities that could result in loss of the vehicle and a range safety hazardous condition. It was our understanding that other aspects of the analysis to determine the overall risk from launch of a mission such as Galileo, including the definition of accident environments and the behavior of the RTGs under such conditions, were being performed under other contracts.

As part of their advisory capacity to the Department of Defense representative to the Interagency Nuclear Safety Review Panel, the Air Force Weapons Laboratory, in 1983, contracted with Teledyne Energy Systems, Inc., to review the work done by Wiggins. Teledyne, in turn, subcontracted the work to Sierra Energy and Risk Assessment, Inc. (SERA).[5] The results of SERA's limited review raised serious questions regarding the accuracy of the vehicle failure probability estimates and the utility of the Wiggins' results for assessment of risk for missions involving radioisotopic thermoelectric generators.

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As a continuation of their independent evaluation of range safety, the Air Force Weapons Laboratory requested that Sandia National Laboratories further investigate and evaluate the issues raised by Sierra Energy and Risk Assessment.

Study Objectives and Scope

The objectives of the Sandia study were to independently review the work of the J. H. Wiggins Company and Sierra Energy and Risk Assessment, Inc., to:

1. Identify the major differences between the vehicle failure probability estimates;

2. Develop an informed opinion of the merits of each work;

3. Evaluate the potential importance of various issues; and

4. Formulate an independent opinion of the vehicle failure probabilities, if possible.

The work was conducted over a two-month period. Resources did not permit a full, independent review of the original range safety hazards analysis to identify additional issues; nor did they permit an independent calculation of vehicle response probabilities. Rather, this work consisted primarily of a review of the issues raised in the SERA report.

Sierra Energy and Risk Assessment concluded that vehicle failure probabilities as estimated by Wiggins are substantially low, perhaps by up to a factor of 1000 in some instances. This was attributed to a number of issues including the estimate of the failure probability of the solid rocket boosters, the techniques used for calculating the probabilities of other modes of vehicle failure, and limitations and omissions from Wiggins' analysis.

Solid Rocket Booster Failure Rates

Both Wiggins and SERA identified solid rocket booster failure as the dominant failure mode to the mission. Both reports discussed the treatment of solid rocket booster failure data in considerable depth. In contrast to the other modes of vehicle failure, failure of the solid rocket boosters was treated as a single system failure. The failure rate was estimated from experience with earlier solid rocket boosters. Wiggins' and SERA's estimates differed by more than a factor of ten. Central to the discussion was whether and how to incorporate "learning" into the analysis; that is, whether and how the failure rate has decreased as more experience with various types of solid rocket boosters has been obtained.

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Wiggins argued that present solid rocket booster failure rates are less than historical data would indicate. This was based on a judgement that solid rocket technology has improved over time. The report, however, provided no analytic justification for this judgement.

SERA evaluated the historical data, but their approach would bias the failure rate estimate upward if technology has improved over time.

Our review of the data suggests that learning may be important to the failure estimate. We developed a statistical approach that incorporates learning, if it exists, into the failure rate estimate.[6] However, in the absence of more specific information regarding failures of various historic rocket systems, we were unable to develop an independent estimate of solid rocket booster failure.

Estimates of Other Modes of Vehicle Failure

SERA raised a number of issues concerning the techniques used for estimating the probabilities of other modes of vehicle failure. To evaluate these issues, we constructed an example simulating one vehicle failure mode from the Wiggins' analysis. By varying appropriate parameters in the model, we gained insight into the possible quantitative effects of these issues.

Our review suggests that several of SERA's criticisms are valid. However, their claim that the estimates of vehicle failure were several orders of magnitude too low was not supported by our review.

Our analysis showed that of the methodological issues raised, only two were likely to substantially influence the failure probability estimates. The first was SERA's view that there exists considerably more uncertainty in component failure rates than Wiggins assumed. However, our review concluded that there was not an adequate basis in the SERA report for their view. Second, SERA argued that failure rate multipliers should be used to account for environmental influence on failure rates. We concluded that there was precedent for use of failure rate multipliers in other related studies that provide input to the mission-safety analysis. Several other issues were examined, but they appeared to have only modest impacts on the results.

Although we did not develop an alternative estimate of vehicle response mode failure probabilities, we found no reason to believe that a reevaluation considering these issues would increase the estimate of failure probability by a factor of 1000.

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Omissions from the Wiggins' Analysis

SERA identified a number of areas not treated by Wiggins. These include:

common-mode failures
maintenance errors
mission personnel errors
common-cause failures
ground-equipment failures
software errors
preexisting failures

A number of these omissions were acknowledged by Wiggins in their reports and appear to be beyond their defined scope of analysis. SERA concluded that if these contributors to risk were included in the analysis selected vehicle failure mode probabilities would increase by a factor of 10 to 100.

We concluded that some of these factors may well contribute to the risk of the mission and, at the least, need improved justification for their omission. Yet we found little support for SERA's numerical estimate and have no reason to believe that such an increase in overall vehicle failure probability would occur, particularly if failure of the solid rocket boosters were to remain the dominant failure mode.

Conclusion

In summary, Sandia's review identified some technical deficiencies and some areas in which more justification would improve the Wiggins' reports credibility and traceability. SERA identified several shortcomings in Wiggins' reports, not all of which were previously acknowledged by Wiggins but several of which apparently were outside their scope of work. On the other hand, we do not believe that SERA adequately supported their conclusion that current probability estimates could be low by several orders of magnitude. Neither Wiggins nor SERA convincingly estimated the probability of the dominant failure mode, solid rocket booster failure. We presented an improved statistical approach to estimating the solid rocket booster failure rate. Although the possibility of significant error in Wiggins' estimate of vehicle failure probability remains, our evaluation of methodological issues provided no evidence of such large underestimates.

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Mrs. LLOYD. Thank you, Dr. Carlson. Mr. Casani.

Would you tell me how to pronounce your name correctly?

Mr. CASANI. Yes, Madam Chairman, my name is pronounced Casani.

Mrs. LLOYD. Casani. Thank you very much.

Mr. CASANI. Thank you for your courtesy of inquiring.

Madam Chairman, Mr. Nelson, and other members of the committee, I have a prepared testimony, which I would like to submit for the record, if you will accept that.

Mrs. LLOYD. It will be made a part of the record, and you may summarize as you wish.

Mr. CASANI. Thank you kindly. I appreciate the opportunity to appear before all of you this afternoon to discuss the use of RTG's in planetary exploration, especially as it relates the Galileo mission to Jupiter. In my discussion or testimony, I will touch briefly on why we use RTG's on some of our spacecraft. I think that has been touched on by several witnesses this afternoon, so I need not dwell on that, and explain what our management and technical roles are in the use of RTG's on the spacecraft.

As you are aware, JPL's principal role for NASA is to conduct the systematic program of exploration of the solar system with unmanned spacecraft, and in performing this task we have sent a lot of spacecraft to nearly all of the planets in the solar system, most recently Uranus.

As these spacecrafts have been targeted further and further from the Earth, we have had to rely more on RTG's to supply electrical power, and in fact, as it has been touched on in earlier testimony, RTG's are the only way of providing electrical power for spacecraft going to the outer planets, and that is to meet the objectives set by NASA. RTG's are really indispensible.

Now, the roles of NASA and the DOE on the joint program are set forth in an interagency memorandum of agreement. Fundamentally, the DOE is responsible for building the generators and for doing all of the relevant safety analyses, aerospace nuclear safety work, while NASA provides the spacecraft and all of the supporting integration functions. JPL's role in supporting NASA is to define the mechanical electrical thermal interfaces for the RTG's and their use on the spacecraft, and to specify the environmental requirements. What are the test environments the RTG's would need to be submitted to in order to demonstrate their safety and use on the spacecraft.

Our job is to not only specify those things, but also to follow up in the management and the review process to make sure that in the implementation of those interface requirements that they are met within the established standards of reliability safety and within the scheduled requirements. Now the next section of my testimony touches on the way in which the use of RTG's affects the spacecraft. I am going to touch on that very briefly here in the interest of time, but the purpose of that part of the testimony was to describe for you that we don't simply pick RTG's up off a shelf at the DOE somewhere and slap them on to the spacecraft.

They are in fact an integral part of the design. They are very interactive in the design. They require careful consideration in terms of the thermal interfaces, and mass properties. Galileo is a

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spin stabilized spacecraft, which means it is attitude controlled to during flight, and is controlled by the spinning of the spacecraft. The RTG's provide the inertia, the necessary inertia to maintain that spin vector, and as we use propellant course of the mission, the mass properties of the spacecraft are changed as the propellant is utilized, and we have to mechanically alter the position of the RTG's relative to the spin axis of the spacecraft in order to maintain those dynamical properties.

The structural support of the RTG's are a major consideration in the design of the spacecraft. The spacecraft also requires extensive and very careful design to control the thermal balance of the spacecraft. RTG's are employed in a special way in this respect. They not only give off a lot of heat themselves, they represent a very intense point source of heat. But the excess electrical power that is developed by the RTG's are used to power strategically located electrical heaters throughout the spacecraft, which are operated by relays and under the control of the spacecraft computers to maintain the proper thermal balance in the spacecraft. So the design of these requires a lot of thought and a lot of careful integration.

Radiological health considerations require that the RTG's be put into the spacecraft down at the Cape at the latest possible time in the launch process. Normally, if we are dealing with solar panels or something like that that would be integrated early in the assembly process and tested with the solar panels installed. We would have to find a way around that because of the radiological health considerations.

We see the RTG's for the first time in the integration process of the spacecraft after the spacecraft is at Florida, and in fact the first mating of the RTG's with the spacecraft occurs typically maybe 6 weeks or so before when we do the first hands on mechanical integration and electrical integration. After that initial match mate test, the spacecraft is mated to the Centaur and then the Centaur and the spacecraft are transported to the pad, installed in the orbiter vehicle some 6 weeks or so before launch, the RTG's are not brought out to the pad until maybe 10 days beforehand.

This imposes considerable constraints on the way the system has to be tested and operated, but it is necessary to do that in order to reduce the radiological exposure of the other people working in the vicinity of the vehicle. So going back now to the summary direct from the testimony, what I tried to illustrate in those earlier comments is that the RTG's are a major element, and in order to allow for the proper technical interaction, as well as management visibility and control, DOE participates as a functional element of the Galileo project. While the Galileo project is responsible for the management and implementation of all the activities on the spacecraft side of the RTG spacecraft interface, the DOE is responsible for the implementation and management of all those functions that are on the RTG side of the interface.

As a member of the project, they participate in all the planning activities, the execution and review of all major elements of the project, especially those that involve the RTG's and also in any attendant elements that have an interface or interaction with the RTG's.

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Our job at JPL is to at the highest order specify the system level requirements and specifications for defining all those system level requirements on the RTG's. And as I mentioned earlier, they cover performance, electrical performance, thermal performance. They cover testing requirements. They cover interface design. These requirements are documented and approved by both JPL and DOE and are maintained under formal configuration control throughout the life of the project.

Detail specifications for RTG design manufacture and production are developed by the DOE and their contractor, General Electric. A verification that the specification requirements are met is provided through the mechanism of design reviews, qualification and acceptance testing, all of which are reviewed and approved, both JPL and DOE.

Now, we talked a lot today about aerospace nuclear safety, those aspects of safety that are connected with a mishap in flight and the potential release of material, but there is a whole other spectrum of safety activities that are ongoing that have to do the safe use of these in flight. We have got to be very sure that RTG doesn't break off inside the cargo bay, and that sort of concern applies to other elements of the spacecraft as well. We have to be concerned about the safe handling and the radiological aspects of that.

In order to determine that those issues have been properly considered and folded into the design, there are a series of phased safety reviews that are conducted by KSC and by JSC; JSC for the flight safety aspects of the generator, and KSC for the conduct of operations at KSC. Because of the unique hazards of RTG's in terms of radiological safety, these reviews for Galileo and for Ulysses have received added attention, I might say, and I also might say that the space safety reviews, both with KSC and JSC have been completed and successfully completed.

I think I touched adequately on the handling concerns. It is necessary that we pay particular attention that the RTG's are handled in such a way to minimize the health hazards to the technicians and people working with the hardware. We do this by developing detailed procedures using dummy RTG's; that is RTG's that are physically identical or similar to the live RTG's. We go through a very careful step-by-step process, developing those procedures, watching how long it takes to integrate, how far away the people are, and the handling of the generators and for what length of period of time and play that information back against the known radiation, a field that is produced by the generators to make sure that they are under no conditions where we have to expose anybody to more than the minimum standards required.

I might conclude by saying that at KSC—KSC is a NASA center that is responsible for the acceptance and handling of the generators. They provide for the storage facilities. They provide for the safeguarding and protection of the generators while they are at KSC, and they provide for the procedures and provisions that would be necessary to recover the RTG's if an emergency landing site was necessary.

We work closely with them in their developing the requirements on those facilities and the development of those procedures. So

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with that, Madam Chairman, and Mr. Nelson, I conclude my remarks, and I stand ready to answer any questions you might have.

[The prepared statement of Mr. Casani follows:]

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STATEMENT OF

JOHN R. CASANI
GALILEO PROJECT MANAGER

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

before the

SUBCOMMITTEE ON SPACE SCIENCE AND APPLICATIONS, AND
SUBCOMMITTEE ON ENERGY DEVELOPMENT AND APPLICATIONS
COMMITTEE ON SCIENCE AND TECHNOLOGY

Madame Chairwoman, Mr. Chairman, and Members of the Subcommittees:

I appreciate the opportunity to appear before you today to discuss the use of radioisotope thermoelectric generators (RTGs) in planetary exploration, especially as they apply to the Galileo mission to Jupiter.

I will discuss generally why we use RTGs on some of our spacecraft, and explain our management and technical roles in integrating the devices on our spacecraft.

As you are aware, JPL's principal job for NASA is to conduct a systematic program of exploration of the solar system with unmanned spacecraft. In performing this task, we have sent spacecraft to the Moon, to Mercury, Venus, Mars, Jupiter, Saturn, and most recently, Uranus.

As our spacecraft have been targeted to more distant destinations, we have relied more on RTGs to supply spacecraft electrical power. RTGs are, in fact, the only generators capable of providing electrical power to spacecraft traveling to the outer planets. Thus, to meet the objectives of scientific exploration set by NASA, RTGs are indispensible.

The roles of DOE and NASA on a joint program involving a radioisotope power source are defined in an Interagency Agreement prepared by the two agencies. Fundamentally, DOE provides the RTG and is responsible for the safety analysis and safety test program; NASA provides the spacecraft and the attendant integration function and provides the necessary hardware interface and spacecraft environmental data for DOE.

JPL's role relative to the use of RTGs on space projects includes: the definition of mechanical, electrical, and thermal interfaces; the handling of RTGs and their installation on the spacecraft, and; the necessary management

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and technical overview of RTG development to ensure that interface requirements are implemented according to the required standards for safety and reliability. The conduct of the Voyager and Galileo projects relating to RTGs typify this role. Before continuing with the description of JPL's responsibilities relative to the use of RTGs, I would like to describe some of the considerations and consequences of using RTGs on the Galileo mission. Although this discussion will be specific to Galileo, it is generally relevant to any planetary mission.

THE USE OF RTGs ON GALILEO

The Galileo mission to Jupiter will send a spacecraft to orbit Jupiter and conduct long-term, close-up studies of its moons. The spacecraft will also carry a probe that will parachute into the planet's atmosphere to determine its composition.

The Galileo spacecraft carries two RTGs mounted on booms that unfold away from the main spacecraft structure after launch. Together, they provide about 500 watts of electricity to run the instruments and subsystems. While the electrical requirements to operate the spacecraft are not great, they are more than those that could be provided by any other power system, given weight, volume, and lifetime requirements. As cited in other testimony, a solar panel large enough to convert the dim sunlight available at Jupiter's distance from the Sun would be of a prohibitive weight. If, in addition, the mission calls for the spacecraft to operate in orbit around Jupiter, as is the case for Galileo, the solar panel area would have to be increased by nearly a factor of two in order to compensate for the degradation of solar cell efficiency induced by the intense radiation belts around Jupiter.

RTGs are smaller and lighter than solar panels and, in addition, obviate the need for batteries to sustain the operation of the spacecraft on the dark side of Jupiter. Nevertheless, they have a signficant influence on the spacecraft design. Their mass, radiation and thermal characteristics significantly affect the spacecraft configuration, the design of its temperature control system, the integration of the spacecraft into the shuttle, and the flow of hardware in spacecraft assembly and launch preparations.

Structural support for the RTG booms and their deployment after launch, for example, are a major design consideration. Galileo is spin-stabilized and the mass of the RTGs is used to control critical dynamic properties of the spacecraft. Because the spacecraft's attitude in space is stabilized through constant rotation, the components of the spacecraft, including the RTGs, must be balanced around the central axis of rotation. Further, the position of the RTG must be adjusted

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during the flight to account for changes in the inertial properties of the spacecraft due to the depletion of propellants.

Low-level emissions of gamma and neutron radiation from the RTGs could possibly interfere with measurements by Galileo's sensitive instruments; terefore, the RTGs are mounted on booms on the opposite side of the spacecraft facing away from the science instrument platform.

In addition to providing electrical power to operate the spacecraft, the RTGs supply power to critically located heaters that maintain spacecraft and subsystem temperatures.

Radiological health considerations require that the RTGs be mated to the spacecraft as late as practical in the pre-launch process. Consequently, provisions have been made to mount the generators on the spacecraft about 10 days before the opening of the launch period. This occurs several weeks after the spacecraft and the Centaur upper stage have been installed in the orbiter cargo bay, thereby minimizing radiation exposure to the ground crew in accordance with governing safety regulations.

Once installed, care is taken to remove heat produced by the RTGs during launch preparations and after launch. Each generator produces approximately 4 kilowatts of thermal energy that must be removed while the spacecraft is on the pad, and during launch, ascent and early orbit phases.

The shuttle's cooling system has been adapted to provide ascent and on-orbit cooling of the RTGs. Ground cooling equipment is used during the pre-launch phase.

PROJECT MANAGEMENT

My foregoing comments illustrate that the RTGs are a major element of the Galileo spacecraft. In order to allow proper technical interaction as well as management visibility and control, DOE participates as a functional element of the Galileo Project organization. The Galileo Project at JPL is responsible for the management and implementation of all activities on the spacecraft side of the spacecraft/RTG interface, while the DOE is responsible for the management and execution of all activities on the RTG side of the interface. As a member of the Project, DOE participates in the planning, execution and review of all major Project activities that involve RTGs and their attendant elements of the spacecraft and launch system.

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RTG SPECIFICATIONS AND TEST REQUIREMENTS

System-level specifications applying to the RTG are developed by JPL for the purpose of defining the spacecraft system-level requirements on the RTGs. These specifications cover performance, environments, testing requirements and interface design, and are contained in documents that are mutually approved by JPL and DOE and maintained under formal configuration management. Detail specifications for the RTG design, manufacture and testing are developed by the DOE RTG systems contractor (General Electric) for the purpose of providing the delivered product. Verification that specification requirements are met is provided by design reviews, qualification and acceptance tests, and supporting analyses, all of which are jointly reviewed by DOE and JPL for compliance.

PHASED SAFETY REVIEWS

DOE participates with JPL in the phased safety review process required by the Johnson Space Center and the Kennedy Space Center. These are the standard series of reviews required for all shuttle payloads and for the conduct of all project operations at KSC. The reviews inform the Johnson Space Center and the Kennedy Space Center of potential flight and ground hazards, and methods by which the controls are verified to be adequate. Because of the unique hazards of RTGs, including heat and radiation, special attention has been devoted to the safety aspects of this device in ground operations as well as in flight. For Galileo, the phased safety reviews have been successfully completed.

RTG HANDLING

The safety considerations of RTGs as they concern radiation exposure of personnel receive special attention. JPL is responsible for assuring that the handling and installation of the RTGs is consistent with approved radiological health and safety procedures and criteria.

Detailed operations procedures and equipment for handling RTGS are developed by JPL. These procedures are approved by DOE, JPL and the Kennedy Space Center. Extensive personnel training in the execution of these procedures is carried out using full-scale models of the RTGS and spacecraft.

In support of this procedure development, analytical models of the radiation fields produced by the RTGs are developed and verified by measurement on real RTGs. These models are used to estimate the radiation exposure to personnel, and to establish controls for operations around the RTG to minimize such exposure. Actual exposure is controlled by personnel access limits and personal dosimetry measurements to ensure that governing requirements are met.

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KENNEDY SPACE CENTER RESPONSIBILITIES

As the NASA center responsible for the conduct of launch and landing site operations, the Kennedy Space Center provides the services necessary to perform the special tasks of assembly and launching a spacecraft with RTGs. In addition to the control and monitoring of RTG procedures, Kennedy Space Center radiation protection personnel are deeply involved in the early planning activities to ensure that levels of exposure are as low as reasonably achievable. During launch site preparations, Kennedy Space Center provides a dedicated facility for performing RTG receiving, pre-launch operations, and storage.

In addition to standard protection provided for NASA projects, KSC provides the security and safeguards required to ensure the nuclear material is controlled to meet DOE requirements.

If it were necessary to return the payload to a contingency landing site, KSC is responsible for providing the overall coordination and management of the activities at that site. These planning provisions include the necessary procedures and equipment to safely remove the RTGs and return them to DOE.

Madame Chairwoman and Mr. Chairman, I have attempted to give you a comprehensive overview of the use of radioisotope thermoelectric generators on a project of planetary exploration. This concludes my testimony, and I would be pleased to answer any questions you may have.

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Mrs. LLOYD. Thank you, Mr. Casani. All three of you gave very excellent testimony.

Dr. Zocker, now that the flight has been indefinitely postponed, you think there are any safety experiments that need to be done on the RTG safety issues?

Dr. ZOCKER. I believe the safety testing that was performed in support of the analysis work intended to launch those vehicles encompassed the range of potential environments that the units could be exposed to. I also believe that you now have an extraordinary amount of added information. That added information has not evolved to the point where it can be acted upon at this time, but certainly everyone that has given you testimony relative to that particularly aspect of that unfortunate accident has effectively said the same thing; that we will analyze, first of all, and fix what went wrong.

Then second we will look to see what environment really existed in that accident and what you have learned as a consequence of that accident. I think that is a very important element. I think that is a very important element. Once that occurs, I am convinced that any number of pressures will exist to do an additional test. We would be very desirous of doing additional tests to illuminate those areas that you now have perhaps an enhanced concern about, an enhanced understanding about, perhaps in mechanisms and that particular environment that you now have understood well as a result of that accident.

Mrs. LLOYD. I heard that there might be some information we might learn, for instance, on the launch abort situation; that we didn't have enough data on the launch abort situation.

Dr. ZOCKER. I don't think there is an engineer anywhere that is ever satisfied you have done enough tests, and I really feel that you can do refinement; you can do, certainly—you can do more test and indeed have a better confidence level that you understand precisely what is going to occur. You can refine the numbers that was done, and at the December supplement, for example, a closer look—let's see what the consequences——

Mrs. LLOYD. You think we can test, and test, and test.

Dr. ZOCKER. I don't mean just for the sake of testing either. I think all of this——

Mrs. LLOYD. Did you think that a reasonable amount of knowledge will be put together, will be assembled after we learn all about he accident?

Dr. ZOCKER. I believe NASA said that today, the NASA spokesman——

Mrs. LLOYD. I want your opinion, and that is your opinion?

Dr. ZOCKER. I'm sorry?

Mrs. LLOYD. That is your opinion also?

Dr. ZOCKER. Oh, yes, I agree. Right. And I think that it really doesn't have to be stated explicitly. It really is a natural consequence that we have an event that is an unparalleled event, a terribly tragic event, but it certainly has a wealth of information associated with it. You really ought to understand it. You ought to understand the environments and understand much more carefully what those environments have as an implication.

Mrs. LLOYD. Thank you very much.

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Dr. Carlson, it seems from your testimony that you felt that we had more things to learn; look at the SERA study, maybe we have gone a little too far—the Wiggins study might have been a little bit too conservative. Is that correct?

Dr. CARLSON. I think that we saw from our review of the studies that we had too conscientious pieces of work that reached different conclusions, and we thought that there could be more work done if in fact the postulation of learning was correct for solid rocket boosters, and there was more work that could be done to better statistically estimate the reliability.

Mrs. LLOYD. What additional work beyond this would you recommend?

Dr. CARLSON. As I stated, we developed a statistical approach which would, if learning existed; that is, if the technology has improved over time with the appropriate date would provide you a more sound statistical answer to that reliability.

Mrs. LLOYD. And you feel that more work would improve our estimation of the failure modes as well as the probabilities assigned to them.

Dr. CARLSON. The question of failure modes is a different question. There were some comments in the SERA report regarding the process by which Wiggins went about establishing the response modes of the vehicle and how it would fail. Our analysis did not look at that in great detail, and I guess our views were that the process posed by Wiggins was a reasonably straightforward one, and one which would reliably produce identification of appropriate failure modes if conducted thoroughly.

Mrs. LLOYD. Thank you very much.

Mr. Casani, there has been some discussion that additional shielding might be necessary around the RTG power system. I know this was considered earlier, and then they decided it was not a good idea. And we understand that we might look again at the radiated shielding.

Mr. CASANI. Well, yes, Madam Chairman, I would like to comment on that.

Mrs. LLOYD. Will you discuss the merits of the report?

Mr. CASANI. Yes, I will. We looked at shielding earlier in the program, a year and a half or so ago, and decided not to move forward with it because at that time it was not a clearly defined or recognizable need. I mean it can improve things and it will improve things under certain conditions, but whether or not the improvement is justifiable in terms of the pros and cons is another question.

Mrs. LLOYD. Is weight an issue?

Mr. CASANI. Well, maybe the easiest way to think about that—everybody thinks, well, gee, if you put a shield up, you are bound to improve the situation, but maybe for just a moment we could try a little thought experiment. For instance, if somebody was going to set off a stick of dynamite in the front of this table, and we were concerned about protecting those cameras down there. Let's ignore the people for the experiment. You might think about what would happen to the cameras with this little explosion going off.

Now, let's say we put a sheet of steel in front of the cameras or a door and set the explosion off. Is the camera going to be safer with

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that piece of steel or that door in front of it? Well, it may not necessarily be safer because the effect of the explosion is transmitted totally more effectively to that door and drives the door with great force into the camera, doing more damage to the camera than you would have if the door were not there. And that is one of the technical issues involving the use of a shield.

We can put some material between the generator and the point of explosion or encapsulate the generator completely, but the shield will be picked up as a result of the blast wave and accelerated into the generator and may cause more damage. So that means that the shield has got to not only—it may have to be designed in such a way that it really is a vault or a safe that after the impact would prevent the release of any material.

Mrs. LLOYD. You have to make sure what the end result will be.

Mr. CASANI. We have to be very sure of what the end result would be, and at the time we decided not to pursue the shield further, it was not clear that—I think we can say without question that it was not shown to be necessary. The results of the—FSAR—analysis were not available at that time, and we had no reason to suspect that a shield was really going to be necessary to make the safe choice to fly the generator.

As everyone has said earlier, we are going to have to go back and revisit that now, and we will take another look at that, and we will examine the benefits and the penalties of including a shield, and if that is necessary or judged to be necessary, it will be seriously considered.

Mrs. LLOYD. Thank you. Mr. Morrison.

Mr. MORRISON. Just a couple of quick questions. Dr. Zocker, I am a little confused. Your work at Los Alamos, you developed some small heater units. They actually contain radioisotopes themselves.

Dr. ZOCKER. It is the same radioisotope.

Mr. MORRISON. But these were not the heater units as described by Mr. Casani which actually used electricity from the RTG. Am I correct in the differentiation?

Dr. ZOCKER. Without answering the total question for Mr. Casani, my understanding would be that there are fixed sources that apply at thermal stabilization--thermal control on the spacecraft supplemented by electrical units which also add on a perhaps a sensing basis, a balance on thermal—but there are fixed units aboard, so-called 1-watt lightweight radioisotope heater units, 100 of those units aboard the total spacecraft.

Mr. MORRISON. So we have more radioisotope use than the clads that are enclosed within the RTG.

Dr. ZOCKER. They just provide thermal energy and are not part of any electrical generation scheme, but they are distributed through the spacecraft.

Mr. MORRISON. Like having a couple of smoke detectors in your house, I suppose.

No one has asked about what the Soviets are doing, and maybe this is best in the classified section, but I presume the Soviets are using more reactors, actually reactors as opposed to conversion units like we are discussing here today. Anyone with experience in watching in that direction of the world?

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Dr. ZOCKER. I am sure that that direction of the world is watched. I'm not privy to the information.

Mr. CASANI. No, neither am I, sir. We do know that one Soviet spacecraft with a reactor on it reentered Canada, of course.

Mr. MORRISON. Rather enthusiastically, as I recall.

Mr. CASANI. That's right. These generators that we are speaking of today are not reactors.

Mr. MORRISON. Yes, I am well aware of that. My presumption was that the Soviets are probably, as opposed to the sophisticated RTG sort of approach, probably hit it over the head, as they do with most things, with probably considerably more power and weight than they would have to have, and probably considerably less concern for public safety, as we have demonstrated through these last several hours.

Madam Chairwoman, I think I have no other questions of this group, and I thank all of you for your testimony.

Mrs. LLOYD. Thank you, Mr. Morrison. Mr. Nelson.

Mr. NELSON. Thank you, Madam Chairwoman.

Dr. Zocker, tell me about the radioisotope heaters.

Dr. ZOCKER. They basically are a unit that is a passive unit using just the decay energy of the isotope to provide locally the instrumentation stabilizing—and I am answering for John Casani in terms of how he uses them, but at least qualitatively, they provide stabilizing thermal input at fixed points on the spacecraft. In addition to that, there are electrical heaters that are employed as well.

Mr. NELSON. That is what you were referring to in your testimony throughout Galileo

Mr. CASANI. No, sir, it was not. We used two types of heater sources on the Galileo spacecraft. One are RHU's, the radioisotope heater units that you just directed your question to Dr. Zocker about, and also electrical heater units where we actually run some electricity through a little heater element to generate heat locally. This type of heat can be turned on and off under spacecraft computer control. It can be used to modulate the total temperature environment on the spacecraft, and we have dozens, literally dozens of these electrical heater units. Their source of electricity comes from the RTG's.

Mr. NELSON. Right.

Mr. CASANI. Now, in addition to that, we have a number of RHU's, radioisotope isotope heater units. These are about the size of your thumb. They are about a half inch in diameter and three-quarters of an inch long. They have got a small amount of the plutonium 238 material imbedded deep within its bolt. It really looks like a bolt, and it is screwed into the spacecraft in strategic locations.

If you were to hold one in your hand, it would be slightly warm. It would give off the amount of heat that is equivalent to a 1-watt light bulb, maybe a light bulb in a flashlight better. We have almost 100 of those units located strategically throughout the spacecraft.

Mr. NELSON. Throughout Galileo

Mr. CASANI. Throughout the Galileo spacecraft.

Mr. NELSON. How about the other spacecraft that we have had, Viking and Pioneer and so forth?

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Mr. CASANI. On Voyager—we had a number of them on Voyager. I cannot speak directly for Pioneer or Viking. Dick, do you know? We had them on Voyager, Mr. Nelson. I don't know about the Pioneer or Viking.

Mr. NELSON. And I take—they are safe enough so that you can hold them in your hand?

Mr. CASANI. Yes, sir, they are safe enough to hold in your hand. You would not want to hold them in your hand very long, but I think you could carry them around for quite a while before you would exceed the allowable dose that is prescribed by the standards on dose.

Mr. NELSON. And if we were worrying about blowing these things up, what kind of hazard are we looking at?

Mr. CASANI. Well, because they are basically powered by the same material that the RTG's are, the health consequences are the same. The situations are considerably different because each one of these has just a very minute quantity of the material in it. Each generator, Mr. Nelson, has the equivalent of 4,000 watts of thermal power, and we are talking about 100 of these devices with 1 watt of thermal power each, so the amount of material is small, plus the fact that these are very rugged small devices and are very able to withstand impacts and overpressure environments to a much greater degree than the generators can.

Mr. NELSON. How rugged?

Mr. CASANI. I think Dr. Zocker has run the test program. He might be better able to respond to that question.

Dr. ZOCKER. The units are, as John indicated, considerably—they are more rugged to damage from external insult than are the RTG heat sources, both of these.

Mr. NELSON. RTG is 2,200 pounds per square inch. What are they?

Dr. ZOCKER. Approximately the same value—well, the same value for overpressure. John touched on one point. They have been impacted at impact velocities that are somewhat higher. They will withstand an impact velocity against a hard surface somewhat in access of the RTG heat source.

Mr. NELSON. But the overpressure is the same.

Dr. ZOCKER. Yes, that is correct.

Mr. NELSON. Now, let's talk about impact. We have been talking today, what would happen if this RTG happened to be struck by something or if it struck something like the launch tower. What do you think about some of the new technologies in protection of tanks; is any tank warfare being applied to protect this RTG from being penetrated by some hard surface? Have you ever looked at that?

Mr. CASANI. Is the question directed to me, sir?

Mr. NELSON. Anybody on the panel.

Mr. CASANI. We have looked at it at JPL——

Mr. NELSON. You have?

Mr. CASANI. Yes, sir, we have. And the problem, of course, is you have to come with a system that will deal both with the overpressure environment, which tends to rip everything into pieces. The generators, which consist of—each generator is powered by a fueled clad. I think you have heard that term before today, and each

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fueled clad is about the size of golf ball, and it contains this ceramic-like material in an iridium clad. Iridium is a metal shell that is welded around the golf ball material to contain it in the event of an impact, and there are 72 of these in each generator, and they are packaged in modules, four to a module, and the module consists of a graphite material.

When you expose the generator to an overpressure, we find that when you get up over 600 or 700 pounds per square inch static pressure, the graphite is stripped off the clads, and you have the bare golf ball, so in applying any kind of protective device, we have to come up with one that will, first of all, stay in tact in the face of the overpressure, and then we need to worry about the fragments and particles of scrap material or whatever that is flying around in the aftermath of the explosion.

The problem with some of the armor devices, again, is the question of how do we get it to stay or maintain its integrity in face of the overpressure insult that it would be the initiating device. It has been looked at, and we have considered it, sir.

Mr. NELSON. Is that something that there is a continued dialog between the Department of Defense and NASA on any kind of new technologies that might be coming out on tanks that might have some application here?

Mr. CASANI. I cannot say that there is a——

Mr. NELSON. Of course, including classified material.

Mr. CASANI. I can't answer that question. I don't know.

Mr. NELSON. Well, the reason I ask it is that I have found that frequently the Department of Defense does not talk to NASA, and NASA doesn't talk to the Department of Defense, and so I want to make sure we are getting everybody together here.

I wish you could check that, and will you let me know?

Mr. CASANI. Yes, sir, I will.

Mr. NELSON. Let me ask Dr. Carlson—in your study—getting back to these confounded numbers—what numbers did you come up with?

Dr. CARLSON. As I stated, we did not develop a set of numbers for the solid rocket boosters or failure modes. We did not have the resources within the constraints at the time, and the information available to accomplish that.

Mr. NELSON. So you just critiqued what was in the other two reports.

Dr. CARLSON. Yes, we looked primarily at what was in the Sierra Energy and Risk Assessment Report, identified a number of issues. We tried to sort those issues out for the Air Force Weapons Laboratory to provide them an understanding of which were potentially the most important issues out of the number that they raised.

Mr. NELSON. So the answer to the question is, yes, you critiqued those two reports.

Dr. CARLSON. That's correct.

Mr. NELSON. All right, in your opinion—do you have an opinion about what probability would have happened if an RTG had been on board the *Challenger*?

Dr. CARLSON. No, I don't have an opinion about that, I'm sorry.

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Mr. NELSON. OK, any of you would like to comment, anything additional that you can think of that would make the shuttle or the RTG safer.

Mr. CASANI. May I comment on your last question?

Mr. NELSON. Please.

Mr. CASANI. That's a question that has been touched on a couple of times this afternoon, and it is a very natural question. What would have happened had there been a generator in the *Challenger* at the time of that accident? It is a question that we need to get a definitive answer to; that is, an answer that is supported by some analytical work. But to do that analysis will require that we get our hands on the specifics of the data involved in that accident.

Although we have requested that, it has not yet been available to us, but I think it will be shortly. I think you can understand that the people who are working with the accident data must focus their attention primarily on what happened, why it happened, and how do we fix it, and the questions that we want the data for are secondary to that primary purpose.

But we do have expert opinion that has been rendered in this area by several different people, and that opinion ranges from the order of a few tens of pounds per square inch to 100 or maybe 200 pounds per square inch, as Mr. Lombardo testified earlier. Now, at the range of up to a few hundred pounds per square inch, the generator would not have released material, and it would have fallen into the ocean, maybe not as a unit, but maybe 18 separate bricks with four modules in it each, but we have no reason to believe from the expert opinion that has been tendered so far that there would have been any breach of those clads and any release of the material.

As I say, that has to be tested by a definitive analysis, and that must await the release of the data that is required to do that analysis, and that will be done. I think you have already asked one of the witnesses earlier that that be reported back to you, and I think that is a reasonable request.

Madam Chairwoman, if I might, you asked several people if there is any additional testing that could be done or should be done that would help address the question of safety, and with your permission, I would like to share my thoughts with you.

Mrs. LLOYD. I would certainly like to hear from you as well.

Mr. CASANI. Well, one of the large uncertainties in treating the analysis, the safety analysis, is exactly what is the proper numbers or proper data to use to describe the environment that is the result of an explosion, let's say of the Centaur inside of the cargo bay. The only data that we have to fall back on is the set of data that was taken in the early sixties from a project that was called Project Pyro. That data was taken for the purpose of siting some of the Apollo facilities at KSC how far to put them from the launch pad in the event of a launch pad accident.

There was several hundred tests run as part of Project Pyro with various size tanks and different configurations involving various types of liquid propellants, including liquid oxygen and liquid hydrogen. There is wide disagreement within the technical community regarding the relative conservatism that are in the shuttle data book specifications which have been drawn from this data. But at

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the same time there is wide agreement within this same community that further research is necessary, and specifically more testing is necessary to define the near field characteristics of liquid hydrogen/liquid oxygen explosions; specifically, what is the nature of the liquid oxygen/hydrogen mixing and explosion characteristics that would result from this type of an accident.

I think, personally, and I think that this opinion is shared by everyone in the field, that a great deal could be gained by some new research and new development testing in this area.

Mrs. LLOYD. Thank you very much. All of you have been excellent witnesses, all the witnesses today, and I certainly want to thank you for your patience and sitting here for the very long hearings. I was trying to put our hearings in proper perspective.

This is the same thing, ladies and gentlemen, as sitting through church and Sunday school twice on Sunday morning. So you have been very patient and understanding.

Mr. NELSON. Well, the preaching has been very good today.

Mrs. LLOYD. And no collection, right?

Well, we thank you for being here, and at this time it will be necessary for us to clear the room in order that we may begin procedures to continue this hearing in closed executive session. The NUS Corp. will be the witness during this session because they have the responsibility for performing the nuclear risk assessments on the Galileo and Ulysses RTG systems.

As a result of an Executive order back in 1977 and presently under review for declassification, I might add, information contained in this study is considered national security confidential, and as such it will be necessary for only individuals who have the appropriate clearance to be in attendance during this hearing. So we do ask your cooperation. We apologize for the inconvenience it may cause some of you, but we will have to reconvene in about 20 minutes.

At this time, I do ask unanimous consent that the subcommittee close the hearing and resolve itself into executive session to receive testimony of a classified nature involving national security information. Without objection, so ordered. We stand in recess.

[Whereupon, at 6:14 p.m., the committee was adjourned to reconvene in classified executive session.]

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REVIEW OF RTG UTILIZATION IN SPACE MISSIONS

TUESDAY, MARCH 4, 1986

HOUSE OF REPRESENTATIVES, SUBCOMMITTEE ON ENERGY RESEARCH AND PRODUCTION, AND THE SUBCOMMITTEE ON SPACE SCIENCE AND APPLICATIONS, COMMITTEE ON SCIENCE AND TECHNOLOGY,

Washington, DC.

The subcommittees met pursuant to other business at 6:40 p.m., in room 2318, Rayburn House Office Building, Hon. Marilyn Lloyd (chairman of the Subcommittee on Energy Research and Production) presiding.

Mrs. LLOYD. The subcommittee will come to order.

We would like to welcome at this time Mr. Denham, who is vice president of NUS Corp. Also testifying is Dr. Richard Englehart of NUS Corp. Gentlemen, we have your complete testimony. You may proceed as you wish.

STATEMENT OF ROY S. DENHAM, VICE PRESIDENT AND GENERAL MANAGER, ENVIRONMENTAL SERVICES DIVISION, NUS CORP., ACCOMPANIED BY DR. RICHARD W. ENGLEHART, SENIOR EXECUTIVE CONSULTANT, NUS CORP., AND ROY P. LESSY, JR., COUNSEL, MORGAN, LEWIS & BOCKIUS, WASHINGTON, DC

Mr. DENHAM. Thank you, Madam Chairman. I am Roy Denham. With me on my immediate left is Dr. Richard Englehart, who will be presenting testimony. Also with me is Mr. Roy Lessey, legal counsel of the firm of Morgan, Lewis & Bockius, formerly with the Nuclear Regulatory Commission.

I am the vice president of NUS Corp., the general manager of NUS Environmental Services Division. Among the work performed by that division, as you know, is a contract with the U.S. Department of Energy for technical support services for environmental safety and risk assessment relating to the Radioisotope Thermogenerators Program. Under this contract, as has been discussed earlier today, NUS performs radiological dose analyses and prepared a risk assessment document which was incorporated in the final safety analysis report for the Galileo and Ulysses missions.

Dr. Englehart is NUS project manager for this contract and is principal investigator for the study. I will turn this over immediately to him to describe the work done by NUS.

Dr. ENGLEHART. Madam Chairman, Mr. Chairman, NUS was tasked to perform a radiological assessment and to provide a nucle-

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ar risk assessment document, which is volume 3 of the final safety analysis report for NASA's Galileo and the European Space Agency Ulysses mission. This document is in two books, one of which is currently classified confidential national security information.

In my statement, I will cover the objective of the risk assessment, provide a description of the steps in performing the assessment, and I will describe how the results are expressed. Few activities are without some risk. The purpose of the NUS work was to provide a numerical quantification of mission risk. As input to the analysis, General Electric Co. considered a variety of mission accidents scenarios, probabilities and estimates of radioactive material release given an accident, and calculated a probability weighted source term.

These source terms consider the ranges and probabilities of potential accidents and their severities. NUS used these source terms and calculated consequences considering all meteorological conditions; that is wind speed direction and atmospheric stability, and weighted the results according to the probability of the meteorological condition.

The end result of these calculations is a set of numbers which are estimates of the added risk to any potentially affected individual until the launches are successfully completed. These numbers can be compared to other risks which are a part of modern society. Thus, the risk estimates are intended to be input to the safety review component of the launch approval process.

Missions are considered in separate phases since the accident scenarios in potentially affected populations are different as are the calculational models which are used to analyze the consequences of a radioactive release. These phases are pre-launch; that is, during the fueling of the launch vehicle, the first stage ascent during the first 128 seconds, the second stage ascent, which is 128 seconds to 534 seconds and is the time period when the shuttle main engines are firing, but the solids have dropped off, orbit and then trajectory insertion.

The General Electric Co. provided a probability weighted source term which included the quantity and characteristics of the radioactive material release for each mission phase. NUS applied calculational models to these releases to estimate the movement of the material in the environment considering variations in environmental conditions. The form of the material after release is a particulate.

Accident scenarios which might release material involve explosions. Therefore, the modeling generally involves atmospheric transport of particulates. Since the most significant pathway by which a radiation dose can be delivered to people for this material is through inhalation, only a small percent of the total source term which is small enough to be inhaled is generally important in the calculation.

Other radiation dose pathways were included in the calculations as well. Depending on the location of the accident, these pathways include the ingestion of contaminated seafood or vegetables or inhalation of resuspended material after ground deposition. Data bases which were used in these calculations included Kennedy

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Space Center meteorological data, launch area regional demographics, worldwide atmospheric and meteorological data, and demographic data, food production and consumption data and fuel material environmental behavior information.

Once material is inhaled or ingested, some of it can be retained and redistributed within the body. The symmetry model is applied which calculates the transport and dose delivery to the various organs of the body over a period of time. This model was specified by the Interagency Nuclear Safety Review Panel, Biomedical and Environmental Subpanel. The doses which were calculated were those which would result from the initial exposure to the material through inhalation, as well as those from continued exposure to the material through ingestion of contaminated food and resuspension inhalation over a period of 1 year.

This dose is actually delivered over the time the material was retained within the body. For the purposes of the calculation, this period was taken to be 50 years for all individuals. Because of decreasing invironmental availability of the material, the contribution due to exposure to inhalation and ingestion in subsequent years is much reduced. No credit was taken for possible protective actions which might be taken in case of an accident such as sheltering or food restrictions.

The next step in these calculations was to sum the doses to all exposed persons in order to calculate what is called a population dose for each mission phase. Then a health effects conversion factor, which is based on extrapolation of data from exposures at high dose levels was applied to the population dose, which was committed at low dose levels in order to calculate potential latent fatalities. It should be emphasized that extrapolating from dose results in applying them at low dose levels is generally considered conservative. It represents the upper limit of a range of possible results, and the appropriate characterization of potential fatalities for any mission phase would range from zero to the numbers that we calculated no matter what the population dose is that we would be quantifying.

The potential fatalities are calculated to occur over an approximate 50-year period. The mission phase risk quantification is calculated from the calculated upper limit fatalities. It is the product of the total mission phase accident probability and the calculated fatalities, the product divided by the total number of people at risk. This is the upper limit of added risk to an individual.

Several considerations are appropriate in evaluating the results. These calculations were done only to provide an estimate of risk. In the launch area, the radiological analyses were done with a simplified atmospheric model over all the meteorological conditions and combined by the probabilities of those conditions. Thus, the risk quantification represents no single atmospheric condition. Coastal meteorology is usually very complex. The simplified model that we use would tend to overpredict the consequences. Releases in the upper atmosphere might be distributed globally. In that case, while a greater number of persons would be exposed, the doses to which they would be exposed have been judged to be insignificant.

The following table is a compilation of societal risks to which mission risks can be compared. Discounting motor venicle accidents

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and diseases, risks to accidents in extreme weather conditions are approximately in the range of 10 to the minus 4 to 10 to the minus 7 (10^{-4} to 10^{-7}) to any individual. The following table shows a number of those types of numbers for which then the results of our calculations can be compared.

I brought along with me today a view graph showing the results of those computations, which I could put up on the screen there, if you are interested.

If you can see that viewgraph, it shows for the Galileo mission above and the Ulysses below, for each mission phase, which I described earlier, zero through 4, the total accident probability for that phase, the population that was calculated at risk, and the last column shows the added risk to any individual. The maximum risk to any individual for any of the mission phases for both missions was the number at the bottom of the screen.

[The information follows:]

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INDIVIDUAL RISK OF EARLY FATALITY BY VARIOUS CAUSES[A]

ACCIDENT TYPE	TOTAL NUMBER FOR 1969	APPROXIMATE INDIVIDUAL RISK EARLY FATALITY PROBABILITY/YR[A]
MOTOR VEHICLE	55,791	3×10^{-4}
FALLS	17,827	9×10^{-5}
FIRES AND HOT SUBSTANCE	7,451	4×10^{-5}
DROWINING	6,181	3×10^{-5}
POISON	4,516	2×10^{-5}
FIREARMS	2,309	1×10^{-5}
MACHINERY (1968)	2,054	1×10^{-5}
WATER TRANSPORT	1,743	9×10^{-6}
AIR TRAVEL	1,778	9×10^{-6}
FALLING OBJECTS	1,271	6×10^{-6}
ELECTROCUTION	1,143	6×10^{-6}
RAILWAY	884	4×10^{-6}
LIGHTNING	160	5×10^{-7}
TORNADOES	118[B]	4×10^{-7}
HURRICANES	90[C]	4×10^{-7}
ALL OTHERS	8,695	4×10^{-5}
ALL ACCIDENTS	115,000	6×10^{-4}
DISEASES	1,750,000	8×10^{-3}

A. BASED ON TOTAL 1969 U.S. POPULATION, EXCEPT AS NOTED.
B. (1953-1971 AVG.)
C. (1901-1972 AVG.)

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Mission Phase	Accident Probability	Population At Risk	Average Added Risk To An Individual*
		[GALILEO MISSION]	
0	2.84E-05	1 E+05	1.24E-08
1	5.31E-05	1 E+05	2.27E-08
2	6.81E-05	3.53E+09	3.63E-14
3	1.69E-04	3.73E+09	6.46E-11
4	2.09E-02	3.73E+09	3.86E-11
		[ULYSSES MISSION]	
0	2.84E-05	1E+05	1.16E-08
1	5.31E-05	1E+05	2.20E-08
2	6.81E-05	3.53E+09	3.46E-14
3	1.69E-04	3.73E+09	1.08E-10
4	2.09E-02	3.73E+09	6.43E-11

*Maximum Risk to any Individual = 1.13E-07

Mrs. LLOYD. I can't see what the number at the bottom is. Would you read it for us?

Dr. ENGLEHART. 1.13×10^{-7}.

Mr. NELSON. What is 10^{-7}? Is that 1 billion?

Dr. ENGLEHART. 1 in 10 million. It is at the very bottom of the screen, maximum risk to any individual.

Dr. DUGAN. Do these figures match table 17 in the confidential report?

Dr. ENGLEHART. I should have mentioned before, these results are from the supplement to the FSAR, and consider the latest information that DOE had from NASA in updating its shuttle data book and also considered in the case of the Galileo mission, the effects of self-shielding of some of the modules because of the orientation of the RTG.

Mrs. LLOYD. Well, these numbers are larger than the ones in table 17, then.

Dr. ENGLEHART. That's right.

Mrs. LLOYD. But even in your most pessimistic assumption it would be 1 in 10 million that we are exposed.

Dr. ENGLEHART. That is for the closest exposed individual which would be a NASA employee in about 3 miles from the launch site.

Mr. NELSON. Would the lady yield?

Mrs. LLOYD. I yield.

Mr. NELSON. All right, now you have got your different phases there. Mission Phase 0 is on the pad?

Dr. ENGLEHART. Yes, that is the pre-launch period.

Mr. NELSON. That is up through the SRB's.

Dr. ENGLEHART. One is up through the SRB's.

Mr. NELSON. Two is from SRB separation to main engine cutoff.

Dr. ENGLEHART. That's correct.

Mr. NELSON. All right, and then three is what?

Dr. ENGLEHART. Orbit.

Mr. NELSON. And then four?

Dr. ENGLEHART. Trajectory insertion on the trajectory toward Jupiter.

Mr. NELSON. Why is your probability, accident probability greater after you have your SRB separation?

Dr. ENGLEHART. The probabilities were supplied to us by General Electric and in turn, I believe, they got them from NASA and you should direct that question to them, I believe.

Mr. NELSON. Well, where are they? Are they here? Come on up to the mike.

Mr. CORK. The accident probabilities that are shown on that table for the phase 4 include all accidents that would result in a—not in a successful mission completion; that is, not only an explosion, but also a guidance error that might leave the spacecraft in the trajectory that would cause it to reenter the atmosphere. So therefore when you consider that class of system failures that are not necessarily explosions, you get a higher probability than all of the other of the probabilities, and Phases zero through 3 are actually explosion probabilities.

Mr. NELSON. OK, I understand that, but my question is why you have—Marilyn, I'm sorry. You go ahead, and I will finish whenever you are through.

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Mrs. LLOYD. Well, the accident probability is greater, but the exposure is about nil; is that not correct?

Mr. CORK. The result in terms of effect, since the RTG is designed for reentry and therefore a great majority of those accidents in phase 4 would result in no measurable release because the RTG is designed for reentry and therefore it would survive reentry.

Mrs. LLOYD. That was the point I was trying to make. Then it is almost nil because it couldn't happen in that phase. It wouldn't have much radiation. Without radiation you are not going to harm people.

Mr. CORK. That's affirmative, yes.

Mrs. LLOYD. Mr. Nelson.

Mr. NELSON. Don't leave us. I have some more questions for you. I want to know why your accident probability is greater after you separated your solid rockets and you are higher in the atmosphere—I am talking about the difference between mission phase 1 and 2.

Mr. CORK. I can't answer that question other than those specifically are the numbers that were provided by the shuttle data book. And I should, for the record, indicate that these are the numbers that include the 10^{-5} probability on the solid rocket motors. So if one wanted to put whatever English one wanted to on those estimates based on other opinions, that would obviously have a different effect on the results in the situation.

Mr. NELSON. Have we got another answer back here?

Dr. SILVEIRA. Chairman Nelson, I think mainly the difference you see in numbers are between the SRB phase and on the main engine phase is mainly the exposure time that you are in that mode, and that adds up to the difference in numbers.

Mr. NELSON. OK, so we are talking about accident probability, not about probability of humans that are exposed.

Dr. SILVEIRA. Yes, sir.

Mr. NELSON. OK, let me turn back to Dr. Denham. All right, now quantify that in terms of humans dying over a 50-year period, and go through each of the mission phases for us.

Mr. DENHAM. I'm going to give that to Dr. Englehart.

Dr. ENGLEHART. The numbers which those added risks to an individual were derived from are, as you question, calculated fatalities over a 50-year period. For both missions for phases 0 and 1, that number is on the order of 40. For phase 2, that number is on the order of 1 to 2. For phase 3, that number is on the order of 1,400 for Galileo, and 2,400 for Ulysses.

For phase 4, that number is on the order of 6 for Galileo and 12 for Ulysses.

Mr. NELSON. Why does it go up—mission phase 3 is after you have had main engine cut-off; isn't that right?

Mr. ENGLEHART. That's correct.

Mr. NELSON. Why do you get so many more humans affected—mission phase 3 is after main engine cut-off and before what?

Dr. ENGLEHART. Before trajectory insertion.

Mr. NELSON. Before your Centaur burns.

Dr. ENGLEHART. That's correct.

Mr. NELSON. On a Centaur mission would you burn to circularize your orbit before you would release? OK. So you are in your circular

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orbit. Now, why would that affect so many more humans? You said 1,400?

Dr. ENGLEHART. That's correct. The number—and I am going to have to go to General Electric for a description of what the source term, expectation source term derives from, but in terms of the reason a large number is calculated there, is that it results from material being disbursed globally affecting billions of people at very low dose levels, as I described before, and when you multiply those out, and add them up, rather, it becomes an enlarged population dose. And when you apply that health effects conversion factors to that large number, you get a large number as a result.

Now, I mentioned earlier that there are dose levels below which people would judge the results to be insignificant. INSRP mentioned the 50 millirem de minimis number. If you applied that number, those numbers would go away, the numbers in phases 2, 3, and 4.

Mr. NELSON. You said they would go away?

Dr. ENGLEHART. They would essentially be zero.

Mr. NELSON. If you applied what to them?

Dr. ENGLEHART. The de minimis dose level, which is on the order of 1 millirem per year.

Mrs. LLOYD. Pardon me, do you have Galileo and Ulysses mixed up in phase 3?

Dr. ENGLEHART. No, they are correct as stated.

Mrs. LLOYD. Ulysses has one RTG; is that correct?

Dr. ENGLEHART. That is correct.

Mrs. LLOYD. And Galileo has two?

Dr. ENGLEHART. That's correct.

Mrs. LLOYD. Why would they have less on Galileo then?

Dr. ENGLEHART. The effect on self-shield, and I should let GE answer this one, but the source term is less for Galileo because of the orientation of the RTG's within the shuttle. They are hemmed on to the explosion, and there is a self-shielding function there. The Ulysses RTG is crosswise to the explosion, and all of the modules of the RTG would be affected there, whereas in the Galileo, on the first modules would be affected severely, then it would be shielded as you go back.

Mrs. LLOYD. Thank you.

Mr. NELSON. Now, 2 years ago there was a Soviet nuclear reactor that came down over Canada. Can you give me some means of comparison here?

Dr. ENGLEHART. Not at this point. We did a report on that for DOE analyzing the risk at that time. I don't recall what the results were at this point.

Mr. NELSON. Well, is it anywhere on the order of 40 or 1,400?

Dr. ENGLEHART. Mr. Chairman, I would have to go back to my notes and the report to pull that number out. It is not something I reviewed in preparation for this.

Mrs. LLOYD. Could you supply that for the record for us?

Dr. ENGLEHART. Yes; I could.

[The information follows:]

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Department of Energy
Washington, D.C. 20585

April 29, 1986

Honorable Marilyn Lloyd
Chairman, Subcommittee on Energy
Research and Production
House of Representatives
Washington, D.C. 20515

Dear Madam Chairman:

During hearings conducted by your Subcommittee on March 4, 1986, one of our contractors, NUS Corporation, was asked by Representative Nelson to provide information on the risk and potential consequences of the USSR Cosmos 954 reentry over northern Canada. NUS Corporation performed an analysis of this event in early 1983. I am enclosing a copy of this analysis for your use, which has been reviewed and determined to be unclassified.

We believe this information will satisfy your request. Should you need further information, please let us know.

Sincerely,

James W. Vaughan, Jr.
Acting Assistant Secretary
for Nuclear Energy

Enclosure:
NUS Letter RWE-86-015,
March 6, 1986, w/encl.

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NUS CORPORATION
910 CLOPPER ROAD
GAITHERSBURG, MARYLAND 20878-1399
301-258-6000

RWE-86-015
March 6, 1986

Dr. Gary L. Bennett
Office of Defense Energy
Programs and Special Applications
U.S. Department of Energy
Mail Stop B-107
Germantown, MD 20767

Subject: Congressional Hearing Request for Cosmos 954/1402 Information

Dear Gary:

Representative Nelson requested information from me on the risk and potential consequences of the Cosmos 954 reentry over northern Canada; I promised to provide a written response and I am doing so now to you for your transmittal to the subcommittees. I am also requesting that you have a determination made as to whether or not this material needs to be classified.

The first document transmitted to you is a letter from Bart Bartram to you dated January 15, 1983; it contains a comparative "risk assessment" of the reentries of SNAP-9A, Cosmos 954, and Cosmos 1402. Since these reentries either had already occurred (SNAP-9A and Cosmos 954) or were about to occur (Cosmos 1402), the probability assigned to the accident was unity (1.0).

The analysis for SNAP-9A was done considering $^{238}PuO_2$ as a Y compound. Current dosimetry recommended by INSRP would yield results which are different. The reader should also be cautioned not to apply the cancer fatalities per Ci of Pu-238 to current missions not only because of dosimetry changes, but also because of the importance of particle size distributions, location of release, etc.

The consequences of Cosmos 954 were calculated to be as low as they were in large part because of the low population density in the reentry footprint area.

The analysis for Cosmos 1402 considered a random reentry point with a expected population density of 27 persons per square kilometer. Since the actual reentry was over water, the consequences would be much lower than calculated.

The second document is a two page summerization by me of the potential consequences of the Cosmos 1402 reentry if it were to have occurred over land; it includes consideration of the effects of handling radioactivity "hot" structural pieces such as were recovered from Cosmos 954. It contains an inaccurate statement in the third paragraph regarding radioactivity in the upper atmosphere. Later information indicates that fission products were detected at about 40 Km altitude.

Very truly yours,

Richard W. Englehart, PhD.
Project Manager

RWE/jjr

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NUS CORPORATION
910 CLOPPER ROAD
GAITHERSBURG, MARYLAND 20878
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GEC-83-018-RAD
January 15, 1983

Dr. Gary L. Bennett
Office of Special Nuclear Projects
U. S. Department of Energy
Mail Stop B-107
Germantown, Maryland 20767

Dear Gary:

This letter summarizes a preliminary comparative risk assessment of SNAP-9A, COSMOS 954, and COSMOS 1402 in accordance with your request of January 12, 1983. This assessment has been prepared based on reference design information provided by you for each system along with models and analyses presented in References 1 through 3.

1.0 SNAP-9A

On April 21, 1964, a Transit navigational satellite was launched with a Thor Able Star rocket from Vandenberg Air Force Base, California. The payload included a SNAP-9A Radioisotope Thermoelectric Generator (RTG) containing 17,000 Ci of Pu-238. The system failed to achieve orbit and reentered the atmosphere over the island of Madagascar in the Indian Ocean at approximately 11° S. Latitude and 40° E. Longitude. On reentry, the RTG burned up at an altitude of approximately 150,000 feet, resulting in complete vaporization of the Pu-238 fuel. (4)

Worldwide measurements of Pu-238 concentrations in air and soil indicated that by 1971 approximately 80 percent of the SNAP-9A Pu-238 inventory had deposited on the earth's surface. Of this amount approximately 23 percent had deposited in the Northern Hemisphere and 77 percent had deposited in the Southern Hemisphere. (5,6)

The fallout of Sr-90 resulting from nuclear weapons testing in the upper atmosphere has been evaluated as a function of injection latitude with the results shown in Figure 1 attached. (1,2) The fallout patterns are controlled by worldwide atmospheric circulation patterns. A comparison of Figure 1 with the Pu-238 fallout patterns described in References 5 and 6, an injection latitude of 25° S. is indicated for SNAP-9A. This means that although the actual injection latitude of SNAP-9A was 11° S. Latitude, a latitude of 25° S., when used with the high altitude release model described in References 1 and 2, most nearly approximates measured Pu-238 concentrations.

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The time behavior of ground-level airborne concentrations as a function of time after release and release altitude is shown in Figure 2 based on the models presented in Reference 2. A comparison of Figure 2 with information in Reference 5 indicates a modeled release altitude of between 135,000 and 150,000 feet.

An analysis performed in Reference 3 indicates that the high altitude vaporization of Pu-238 at 150,000 feet and 0° latitude would result in an estimated 1.18×10^{-3} excess cancer fatalities per Ci of Pu-238 released. This includes consideration of all population exposure pathways resulting in inhalation, ingestion, and external radiation doses. The relative risk due to injection at latitudes other than 0° Latitude, accounting for actual worldwide distributions of land and population is shown in Figure 3. For an injection latitude of 25° S. Latitude, which best models the SNAP-9A fallout pattern, the relative risk index is 0.32. Therefore, the consequences of the SNAP-9A reentry are estimated as follows:

$$H = (17{,}000 \text{ Ci Pu-238})(1.18 \times 10^{-3} \frac{\text{Cancer Fatalities}}{\text{Ci Pu-238}})(0.32) \qquad (1)$$
$$= 6.4 \text{ Cancer Fatalities}$$

The predicted cancer fatalities are expected to occur over a period of 20 to 30 years following the incident.

2.0 COSMOS 954

COSMOS 954 was a Russian spacecraft designed for ocean surveillance, was placed in a 280 by 255 km orbit inclined at 65 degrees in September 1977. The spacecraft was powered by a 100 kW_t epithermal nuclear reactor with a core composed of 10 to 90 percent uranium and 90 to 10 percent molybdenum. The uranium was enriched to 90 percent U-235. (7)

The normal mission profile for such a spacecraft included a four month operation period in a low orbit (280 by 255 km high) followed by a boost to a long lived (300 years) orbit 965 km high. (3,7)

COSMOS 954 failed to reboost and reentered the earth's atmosphere on January 24, 1978. COSMOS 954 disassembled due to reentry heating, resulting in a fallout footprint of approximately 50,000 km^2 centered at 62° N. Latitude and 105° W. Longitude in northern Canada. An examination of the fallout footprint debris concluded that approximately 80 percent of the reactor fuel had vaporized on reentry with the remaining 20 percent depositing as non-inhalable particulates in the footprint area. The reactor was assumed to be operating just prior to breakup.

A risk analysis of missions similar to COSMOS 954 performed in Reference 3, indicates that the consequences of a reentry are determined by the following equation:

$$H = 0.0516R_i f_1 + 0.236F_1 f_2 \rho + 0.3214F_2 f_2 \qquad (2)$$

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Dr. Gary L. Bennett
January 15, 1983
Page 3, GEC-83-018-RAD

where:

H = Health effects, excess cancer fatalities
R_i = Risk index as a function of injection latitude from Figure 3
f_1 = Fraction of fuel vaporized
ρ = Average population density within the footprint, persons/km^2
F_1 = Fraction of the footprint area on land
f_2 = Fraction of fuel that promptly falls out
F_2 = Fraction of footprint area over shallow ocean

For COSMOS 954 the values used were as follows:

R_i = 1.00 (Figure 3)
f_1 = 0.80
ρ = 1.44 persons/km^2 (data for Cell 61, Reference 1, Volume 3, Table 2.2-8)
F_1 = 1.00
f_2 = 0.20
F_2 = 0.00

Using these values, Equation 2 results in an estimated 0.12 excess cancer fatalities resulting from the COSMOS 954 incident.

3.0 COSMOS 1402

COSMOS 1402 is a spacecraft similar to COSMOS 954 with an almost identical pre-mission profile except that it utilizes a 50 kW_t reactor. The orbital parameters are almost identical. COSMOS 1402 was launched on August 30, 1982 and operated in the low orbit until the reactor was shutdown on December 28, 1982. COSMOS 1402 failed to reboost to the higher orbit, and as a result, it is expected to reenter the atmosphere on January 23, 1983 ± 4 days in a random manner between 65° N. Latitude and 65° S. Latitude.

A risk analysis was performed for COSMOS 1402 similar to that presented in Reference 3 and for COSMOS 954 presented above. The parameter values assumed in the analysis are based on a random reentry from a 65° inclined orbit using Figures 4 and 5 from Reference 1. The assumed parameters for Equation 2 are as follows:

R_i = 1.00 (Figure 3, assuming 0° injection latitude)
f_1 = 0.80 (Same as for COSMOS 954)
ρ = 27 persons/km^2 (Figure 5)
F_1 = 0.295 (Figure 4)
f_2 = 0.20
F_2 = 0.042

In order to use Equation 3, two modifications must be made. First, it should be multiplied by 0.5 to account for the use of a 50 kW_t reactor instead of a 100 kW_t reactor. Second, since the reactor will be shutdown for approximately 26 days

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prior to reentry, a factor should be applied to account for fission product decay. However, since the noble gases and iodines will be released at high altitudes for the most part, and the principal radionuclides contributing to the risk at ground level are Sr-90, Cs-137, and Ce-144, all of which have long half-lives compared to 26 days, no reduction factor has been applied.

Therefore, using Equation 2 with the assumptions described above, the estimated health effects resulting from the reentry of COSMOS 1402 are estimated to be 0.2 excess cancer fatalities over a period of 20 to 30 years following the incident. This extimate could vary by an order of magnitude or more depending on the specific location of the fallout footprint resulting from the reentry of COSMOS 1402.

The above analysis does not include the possibility that a few individuals may approach or pick up pieces of the fallout debris. Although the dose to the maximally exposed individual may be substantial, the average dose to the population within the footprint area would be small.

4.0 Comparative Risk of SNAP-9A, COSMOS 954, and COSMOS 1402

The results above indicated that the estimated risk resulting from the reentry of SNAP-9A, COSMOS 954, and COSMOS 1402 are 6.4, 0.12, and 0.2 excess cancer fatalities, respectively. The differences in risk are due in part to the assumptions identified above relating to injection latitudes and population densities. Although the total Curie inventory of SNAP-9A is much smaller than COSMOS 954 and COSMOS 1402, consideration must be given to the half-lives, inventory, and internal dose rate conversion factors of the radionuclides controlling the risk in each case.

The total radionuclide inventories of SNAP-9A, COSMOS 954, and COSMOS 1402 at breakup are estimated to be 17,000; 407,000; and 12,200 Ci, respectively, consisting of Pu-238 on SNAP-9A and primarily fission products for COSMOS 954 and COSMOS 1402. Pu-238 is an alpha emitter with a half-life of 86.4 years. The fission products associated with the reactors that contribute to the risk are predominately Sr-90, Cs-137, and Ce-144 with half-lives of 27.7, 30.0, and 0.78 years, respectively. The noble gases and iodines are released at high altitude and most of the very short lived radionuclides that account for most of the Ci inventory will have decayed before reaching ground level or shortly thereafter. The inventory of Sr-90, Cs-137, and Ce-144 at breakup was estimated to be 34.8, 38.9, and 1,080 Ci, respectively, for Cosmos and 19.7,19.6, and 545 Ci, respectively, for COSMOS 1402. The fission products are beta emitters with a Quality Factor of 1, while Pu-238 is an alpha emitter with a Quality Factor of 10. (Note: the Quality Factor of alphas has been redefined in ICRP 30 [8] as described further in Reference 2.) The above factors combine to result in a higher risk fro RTG systems with Pu-238 fuel than for reactor systems for the specific scenarios considered above.

5.0 Risk Comparison with Background Radiation Levels

The above risk assessment or SNAP-9A, COSMOS 954, and COSMOS 1402 should be viewed in light of natural background radiation levels and radionuclide inventories in the atmosphere resulting from nuclear weaposn testing in the past.

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The natural background radiation levels in the United States average approximately 125 mrem/yr to the whole body, including 45 mrem /yr due to cosmic radiation, 60 mrem/yr due to external exposure to natural terrestrial radiation, and 20 mrem/yr due to inhalation and ingestion of natural terrestrial radionuclides. Actual radiation at any location on earth will be a function of altitude, and local soil and rock composition. Assuming that the value of 125 mrem/yr is representative of the worldwide average, and assuming a world population of on the order of 3×10^9 persons, the resulting population dose due to natural background radiation is 3.75×10^8 person-rem/yr. Based on a health effects estimator of 120 excess cancer fatalities per million person-rem, based on the BEIR III Report,[9,10] and assuming a linear dose response model, the health effects resulting from natural background radiation would be estimated to be 4.5×10^4 excess cancer fatalities per year. Over a 20 to 30 year period, the period over which fatal cancers would develop as a result of the incidents considered above, an estimated 9×10^5 to 1.4×10^6 cancer fatalities would develop worldwide as a result of natural background radiation.

Within a 50,000 km^2 footprint area that would be associated with COSMOS 954 and COSMOS 1402, the persons at risk would be 7.2×10^4 and 1.35×10^6, respectively, assuming the COSMOS 1402 footprint would be on land. The excess cancer fatalities within these footprints due to natural background radiation are estimated to be 108 and 2,025, respectively. The risks due to COSMOS 954 and COSMOS 1402 both represent about 0.1 percent of that due to natural background radiation.

Since the first nuclear weapons test at Alamogordo, New Mexico on July 16, 1945, approximately 3.6×10^3 Ci of Pu-239 and Pu-240 together have been injected into the atmosphere.[11] SNAP-9A resulted in the addition of 17,000 Ci of Pu-238, representing almost all the Pu-238 in the atmosphere. Hence, SNAP-9A represents about 4.5 percent of all the plutonium initially injected into the atmosphere on a Curie basis as a result of man-related activities. It should also be noted that Pu-238 has a half-life of 86.4 years, while the half-lives of Pu-239 and Pu-240 are 2.44×10^4 and 6.58×10^3 years, respectively, so the Pu-238 will be removed faster from the global environment.

Prior nuclear weapons testing in the atmosphere also resulted in an initial inventory of 1.56×10^7 Ci of Sr-90.[12] This should be compared with and estimated 35 and 20 Ci of Sr-90 resulting from COSMOS 954 and COSMOS 1402, respectively. Hence, the additional Sr-90 due to COSMOS 954 and COSMOS 1402 (potentially) represent about 1.8×10^{-4} and 1.0×10^{-4} percent, respectively

A more comprehensive analysis and report will be prepared on this subject as additional information becomes available related COSMOS 1402. Should you have any questions on the above information, please let R. Englehart or me know and we can arrange a meeting to discuss them.

Very truly yours,

Bart W. Bartram

Bart W. Bartram
Manager,
Radiological Programs Department

cc: R. Englehart
G. Ogburn

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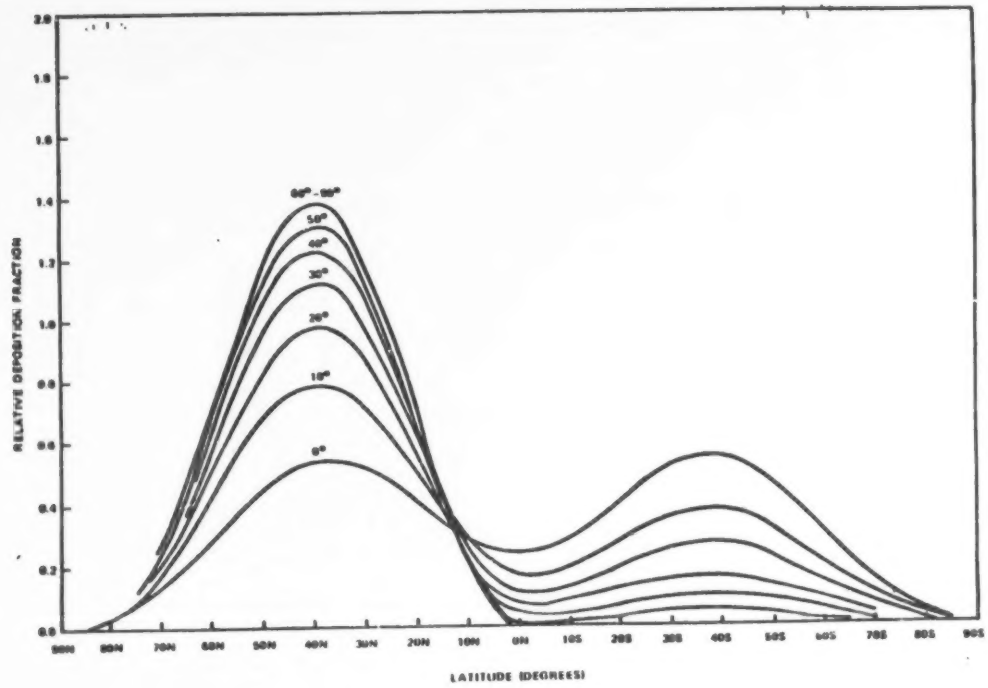

Figure 1 . Deposition of small particles (< 4 μ) released at high altitude as a function of injection latitude. 160

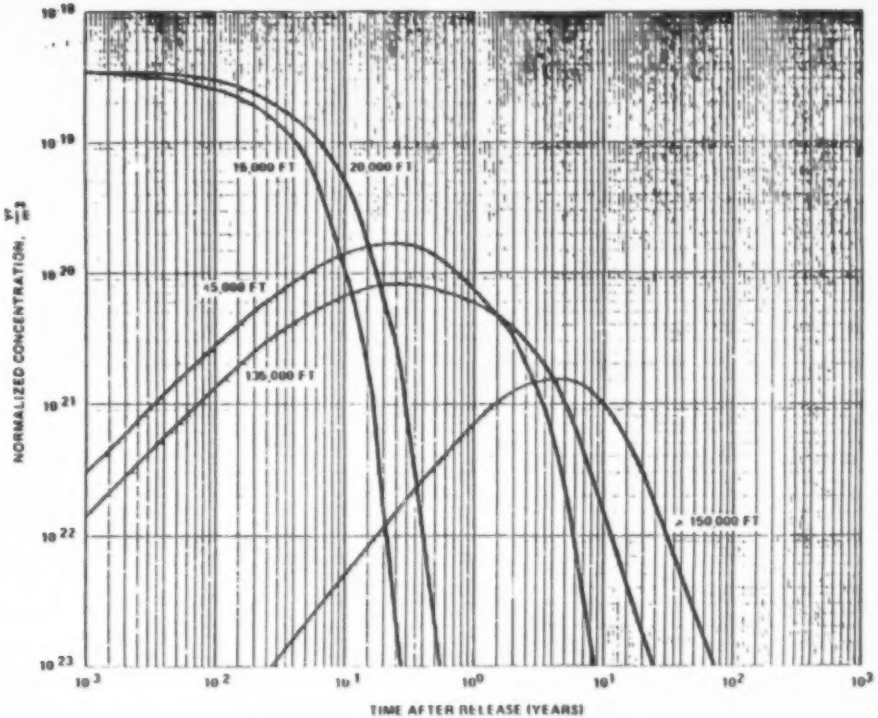

Figure 2. Ground level normalized concentrations for high altitude vapor releases (uniform worldwide distribution).

161

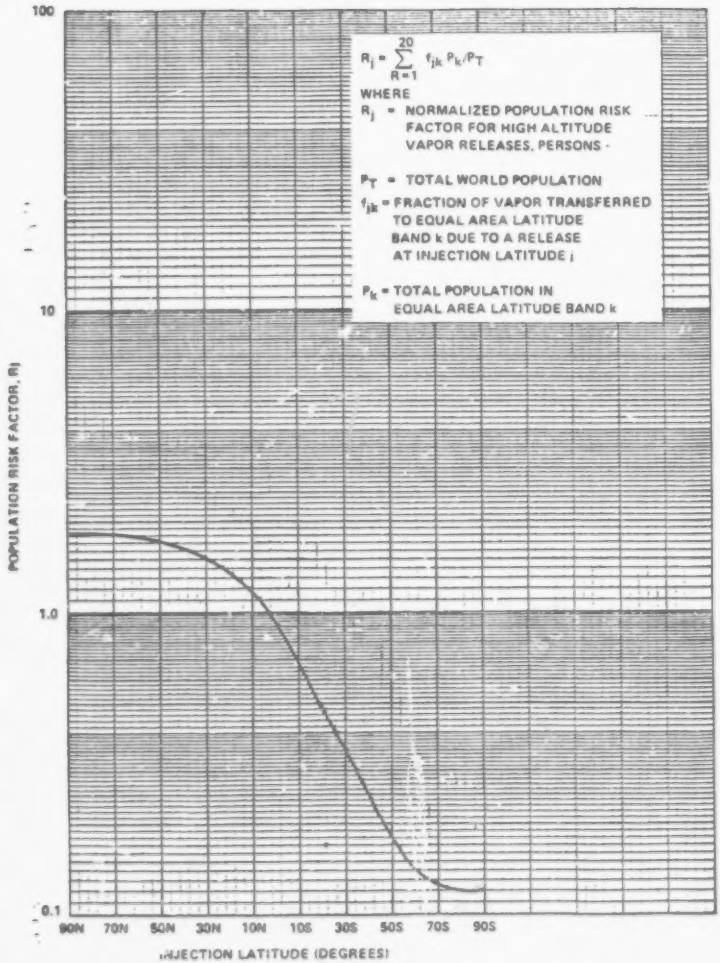
$R_j = \sum_{R=1}^{20} f_{jk} P_k / P_T$
WHERE
R_j = NORMALIZED POPULATION RISK FACTOR FOR HIGH ALTITUDE VAPOR RELEASES, PERSONS
P_T = TOTAL WORLD POPULATION
f_{jk} = FRACTION OF VAPOR TRANSFERRED TO EQUAL AREA LATITUDE BAND k DUE TO A RELEASE AT INJECTION LATITUDE j
P_k = TOTAL POPULATION IN EQUAL AREA LATITUDE BAND k
100
10
1.0
0.1
POPULATION RISK FACTOR, R_j
90N 70N 50N 30N 10N 10S 30S 50S 70S 90S
INJECTION LATITUDE (DEGREES)

Figure 3 Normalized population risk factor as a function of injection latitude for high altitude vapor releases.

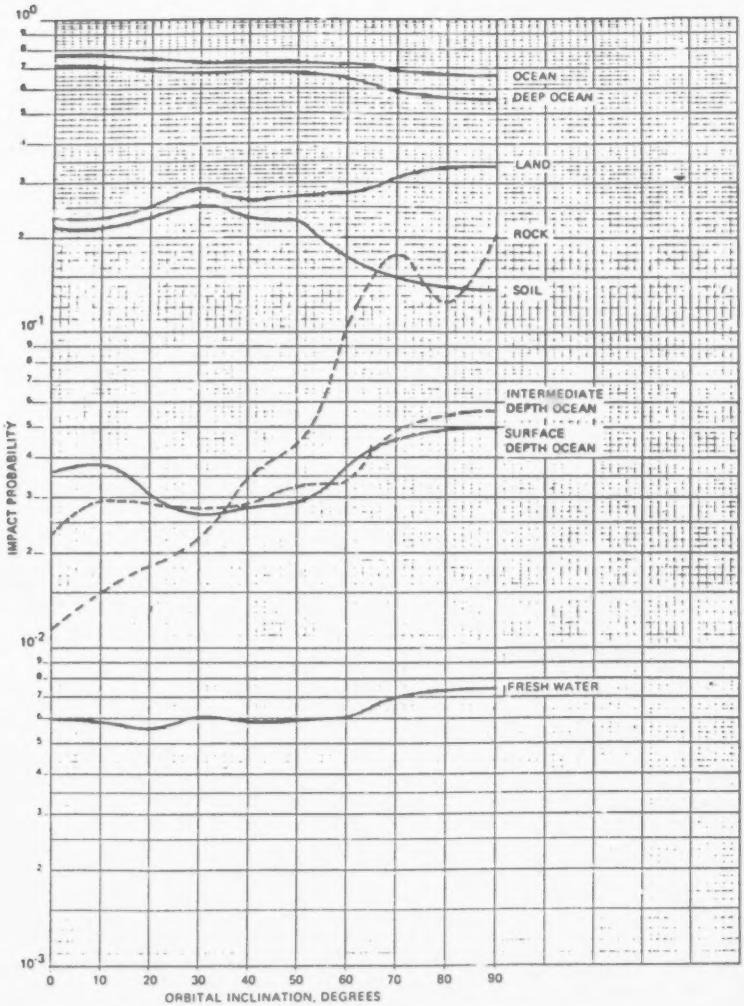

FIGURE 4 RANDOM ORBITAL REENTRY IMPACT PROBABILITIES

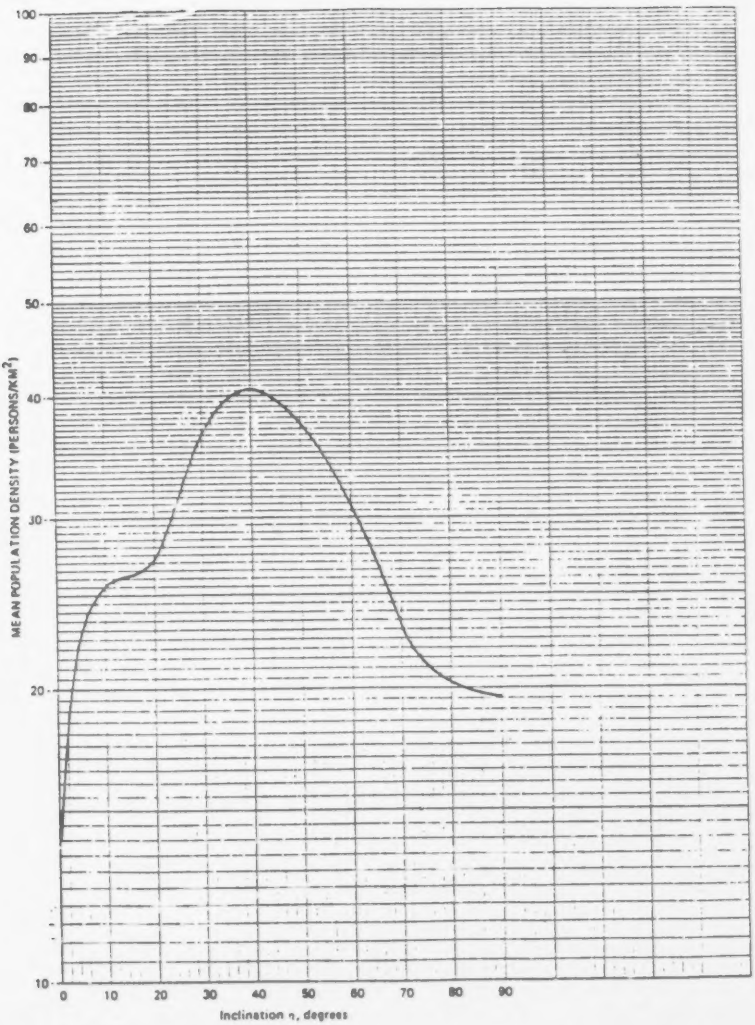

Figure 5 . Expected population density impacted for great circle routes defined by inclination η (land impact probability = 1.0).

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POTENTIAL PUBLIC HEALTH EFFECTS IN THE CASE OF COSMOS 1402 EARTH REENTRY

Preliminary information indicates that Cosmos 1402 is a radar imaging satellite with a nuclear reactor providing electrical power to operate it. It is thought to be the same or similar design to Cosmos 954, which reentered the Earth's atmosphere over northern Canada almost exactly five years ago. Cosmos 1402 is tumbling, apparently out of control, and is expected to reenter the Earth's atmosphere in the later part of January, with the reactor in a shut down configuration.

An estimate of the possible public health impact of a Cosmos 1402 reentry over land areas can be made on the basis of how Cosmos 954 reentered and broke up. The debris from reentry was of two distinct types. The first type was structural and control element pieces which, because of their high melting temperature, reentered intact. There were 49 beryllium pieces found; 33 of them were rods 2 centimeters in diameter and 10 centimeters long, weighing 40 to 50 grams each. There were 6 cylinders 10 centimeters in diameter and 25 centimeters long, each weighing 3.6 kilograms. Other miscellaneous pieces made up a total of 25 kilograms of beryllium found on the ground over an area of about 500 square miles. There may be as much as an additional 100 to 125 kilograms not recovered. These pieces were radioactive with a radiation intensity of from 10 milli Roentgens per hour to 15 Roentgens per hour near their surfaces. The hazards from these pieces are of two types, the danger of being struck by them or secondary missiles from impact (such as breaking glass) and the radiation. If they were picked up, skin and clothes would become radioactively contaminated, requiring washing of hands and disposal of clothing. In addition, prolonged contact over a period of hours could result in radiation burns to the skin.

The second type of debris was fuel particles. The reactor core disintegrated as it reentered; subsequent atmospheric monitoring showed no traces of radioactivity remaining in the upper atmosphere. Only a small fraction of the total estimated mass of the fuel was recovered, over about 20,000 square miles. Almost all of the fuel particles recovered were in the range of 10-100 micrometers in diameter, but a few of them were larger, resembling cinder slag from a furnace. These larger particles were very radioactive, some with a

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radiation field of 500 Roentgens per hour on contact. These would be very dangerous to pick up, with severe radiation burns and injury to anyone in close contact with them for even a few minutes. There were only a few of these recovered, but there could be many more which weren't recovered if they fell into the Great Slave Lake in Canada. The smaller particulates are too large to be inhaled as dust, and too small to create a direct radiation hazard. However, they would represent a large area land contamination from which a long term low level population radiation dose could be delivered primarily through food ingestion and ground plane radiation. The long term radiation impact of these smaller particulates is dependent on the population density (persons per square mile) in the affected area, and the amount of agricultural production.

As a first estimate of the public health effects, it is very unlikely that an individual would be hit by an impacting object (about 50 objects in 500 square miles). It is likely, however, that one or more individuals could handle a high radiation level object out of curiosity before being properly warned. This is estimated to give one to five individuals a 25 rem whole body radiation dose and possibly radiation skin burns. Finally, widespread ground contamination is estimated to result in one to ten excess cancer deaths over a period of 20 to 30 years.

In summary, there are three types of risk from Cosmos 1402 should it reenter over land areas and behave like Cosmos 954. The first is from physical injury caused by sizable impacting pieces. The second is radiation burns which might result if persons pick up these pieces or large (cinder size) fuel chunks. The third would result from the long term population dose from low level land contamination. The overall probability of land impact is about 30 percent. Impact in oceans would involve a much lower public health impact. The probability that any individual will be located within the Cosmos 1402 debris area is estimated to be about 1 in 10,000.

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Mr. NELSON. I don't understand also the humans affected why you have got 40 mission phase 1 and 2; zero for mission phase—correction, 40 for mission phase zero and 1. Then you said zero humans affected for mission phase 2.

Dr. ENGLEHART. Let me clarify the numbers up there. In the population at risk those are the numbers of people within the area of spread of the material that were affected that contributed to the population dose. In phases zero and 1, that is 100,000 in each case. In phase 2, 3, and 4, it is essentially the world's population or about 4 billion people.

The calculated number of fatalities in those populations for phases zero and 1 were about 40.

Mr. NELSON. Right.

Dr. ENGLEHART. By the way, I should also clarify that was zero to 40.

Mr. NELSON. How many humans did you say were calculated in mission phase 2? Did you say zero humans or one or two humans?

Dr. ENGLEHART. One or two.

Mr. NELSON. One or two. And then you said mission phase 3 up to 1,400.

Why the difference, since the whole world's population is exposed in both phases?

Dr. ENGLEHART. In phase 2 the source term provided to us was of such a nature that most of the material either remained as a vapor suspended in the high atmosphere, coming down over a long period of time, or in very large particulates on the order of 2,000 microns. Those are noninhalable particles and would not contribute to the inhalation dose. So most of the material really didn't contribute to the dose, only the portion of it which was in the form of a vapor in the high atmosphere, and that came down over a long period of time.

Mr. NELSON. How would that differ? You are still up high over the atmosphere in mission phase 3.

Dr. ENGLEHART. In phase 3 the source term provided to us was more in the form of vapor and very small particulates which then did a much more—a higher percentage of the source term was an inhalable fraction and affected the world's population.

Mr. NELSON. Why would it be inhalable there and not in the previous phase?

Dr. ENGLEHART. I am going to have to defer that one to General Electric for a description because I just don't recall at this moment why the 2,000 micron particle size for most of the particles and vapor for the rest.

I believe the phase 3 was resulted from—part of the expectation source term resulting from the graphite being blown off of the iridium capsules and the capsules being subjected to melting as they reenter. I really should defer that one to General Electric.

Mr. NELSON. Well, has something changed with regard to the RTG and a change between the two mission stages there?

Dr. ENGLEHART. Let me refer that to General Electric. I think they are better qualified to answer that.

Mr. NELSON. Can somebody answer?

Mr. SINKEWIZ. The difference between phase 3 and phase 4——

Mr. NELSON. No, phase 2 and phase 3.

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Mr. SINKEWIZ. Yes—is the type of explosion that would occur. In phase 3, I think, as I recall, the situation there and the reason the source terms were different than phase 2 is that we had more graphite stripped off of the cladded fuel cells, fuel elements, and therefore there was a difference in how much fuel was available, if you will, to reenter the atmosphere. Whereas, in the other phase of the mission, we did not have that much graphite stripped off of the cladded cell.

Mr. NELSON. What is the reason for the change in the stripping of the graphite when all I can see is the difference of the mission phase is, one you are still in ascent, in powered ascent; and the other one, you are up there in your transfer orbit getting ready to eject your Centaur.

Mr. SINKEWIZ. I think it is a matter—I might have to ask somebody to help me with this, but I believe it was a matter of the explosion—the magnitude of the explosion between the two phases. One phase had—our input that we received was a larger explosion that we applied, and that resulted in more graphite being stripped off.

Mr. NELSON. OK, now you would think that the greater explosion would occur when you had the ET still connected to you in the powered ascent, but your figures are exactly the reverse.

Mr. SINKEWIZ. There is one other factor that I didn't mention, and that is the time factor, how much time you are in orbit, and therefore that increases the probability of occurrence versus shorter period of time when you are in a powered stage.

Mr. NELSON. OK, you would launch Galileo, what, about 6 hours after insertion into orbit?

Mr. SINKEWIZ. I don't know.

Dr. ENGLEHART. One thing that may be confusing the issue is that these analyses are done on the basis of the expectation source terms, and so probability does factor into the source term. It is a probability times the source term for each scenario, and they add all those up and then divide by the total accident probability so that these cannot be traced directly to specific scenarios, so that when you have a probability larger because the phased duration is longer, it does affect the source term.

Mrs. LLOYD. I would like to go back to the confidential chart that was supplied to us. On your table 17 it seems that the indvidual risk is based on 10^{-10}. Is that correct, on this chart?

Dr. ENGLEHART. I'm sorry, I don't have that in front of me.

Mrs. LLOYD. The approximate individual risk for cancer death. Phase 3 is 10^{-11}, and then on your chart there, your maximum risk is 10^{-7}.

Dr. ENGLEHART. Excuse me, I would have to examine what you are looking at to be able to answer the question.

Mrs. LLOYD. But in any indication, it seems that the apparent risks, except for the phase 3, are almost negligible compared to other forms of accidents.

Dr. ENGLEHART. Could you restate the question?

Mrs. LLOYD. While you were looking at it, I just made the comment that except for the phase 3 scenario that the risks are apparently almost negiligible compared to the risk that we experience in

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our day-to-day lives, such as riding a bicycle or riding in a car or walking across the street.

Dr. ENGLEHART. All of the added risks to an individual.

Mrs. LLOYD. Yes, the added risks are almost negligible except in the phase 3 scenario.

Dr. ENGLEHART. Even in phase 3, it is 10^{-11}.

Mrs. LLOYD. But I was wondering why the difference in this chart and the one that was supplied to us in the book, what happened?

Dr. ENGLEHART. Well, the one supplied in the original issue of the FSAR also shows very low numbers in that last column.

Mrs. LLOYD. Well, indeed, they are lower, but there is a disparity in the two. That's what I was concerned about.

Dr. ENGLEHART. Well, phase 3 in what we had supplied originally before the supplement shows 9×10^{-11}, and you are comparing that to phase 3 here of 6×10^{-11}. They are comparable, I would say.

Mrs. LLOYD. Well, what increased the numbers, though? This is 10^{-7}. What increased the numbers——

Dr. ENGLEHART. Excuse me, where do you see 10^{-7}?

Mrs. LLOYD. Up there under the maximum risk.

Dr. ENGLEHART. The maximum risk to an individual at the bottom?

Mrs. LLOYD. Yes.

Dr. ENGLEHART. That is during phase 0, and it is to an individual about 3 miles away from the launch pad who is there for NASA purposes. He is a NASA employee.

Mrs. LLOYD. So this is a difference in the phases then.

Dr. ENGLEHART. Well, the 10^{-7} number is a maximum to an individual during phase 0. It is a launch support person. It should be compared to the number 1×10^{-8}, which is average to the population in general. I'm not sure I understand——

Mrs. LLOYD. But I am not sure why the numbers changed. That's all I asked.

Dr. ENGLEHART. Between the first report and this report?

Mrs. LLOYD. That's correct.

Dr. ENGLEHART. Because the expectation source terms went up generally.

Mrs. LLOYD. Well, why did the source terms go up?

Dr. ENGLEHART. I think I will defer that one to General Electric. It was based on new information supplied by them.

Mrs. LLOYD. It was based on new information supplied?

Dr. ENGLEHART. Yes.

Mrs. LLOYD. General Electric, could you answer why your source terms went up?

Mr. SINKEWIZ. Yes, I believe the single change that caused most of that was the different assumption on the bulkhead in terms of the impact of the RTG's in the bulkhead. I think in one case—the first case was that we assumed the bulkhead did not stay in tact, and in the second case it would stay in tact.

Mrs. LLOYD. Very good. Thank you very much.

Mr. NELSON. Help me square when we say that the maximum risk is 1 in 10 million with the numbers of people, 1,400 maximum fatalities over a 50-year period.

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Dr. ENGLEHART. The risk number is quantified by calculating that number, the 1,400 number, multiply that times the probability of the accident, and divide by the total number of people affected so that the number that you end up with in terms of risk to an individual includes consideration of it is a very improbable event, and those consequences, those 1,400 calculated deaths are over a very large number of people. So the risk to any one person is fairly small for that reason as well.

Mr. NELSON. Even in that phase, which is phase 3, your maximum risk is still 1 in 10 million.

Dr. ENGLEHART. Phase 3 is for Galileo, about 6×10^{-11}, which is 1 in 100 billion—or 6 in 100 billion, and for Ulysses it is 1×10^{-10}, which is 1 in 10 billion.

Mr. NELSON. So which phase is the maximum risk of 1 to 10 million applicable to?

Dr. ENGLEHART. That is phase 0.

Mr. NELSON. Phase 0, so that is on the launch pad.

Dr. ENGLEHART. To a person very close to the launch pad, and that one is calculated by calculating his dose multiplying by health effects conversion factor and multiplying by the probability of the accident.

Mr. NELSON. And you figure that also you are putting in your calculations, the probabilities with an explosion on the pad that you might hit the steel of the launch tower and have the worst case scenario.

Dr. ENGLEHART. That is correct. That is included in the calculation of the probability weighted source term that General Electric provided.

Mrs. LLOYD. Isn't that because there are more people directly involved that would breathe the air?

Dr. ENGLEHART. Would you repeat the question?

Mrs. LLOYD. Well, in phase 0, when you have more people—if there is an accident at that stage, there would be more people there that would inhale the vapors.

Dr. ENGLEHART. Well, of course in the later phases because the material is spread globally, there are actually more people exposed in that consideration than in the launch area.

Mrs. LLOYD. But wouldn't the dose rates be lower, though?

Dr. ENGLEHART. That's correct. Very small.

Mrs. LLOYD. That is the point I was trying to make. The doses would be at greater magnitude.

Dr. ENGLEHART. Doses to individuals would be greater magnitude in the launch area.

Mrs. LLOYD. Thank you.

Mr. NELSON. I want to go back and question your figures. I want you to tell me how you got to 1,400 for phase 3. There are 3½ billion people on the Earth, and if the maximum risk—and you said the risk is even less in phase 3. But let's take the maximum risk—even for phase 3, you said the maximum risk is 1 in 10 million. Then is my math wrong? Isn't that 350 people?

Dr. ENGLEHART. No, phase 3 is 1 in 10 billion.

Mr. NELSON. So it ought to be even less. So how in the world did you get to 1,400 people?

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Dr. ENGLEHART. The 1,400 people are calculating the total population dose and multiplying by health effects conversion factor to get calculated deaths. Then to calculate the risk to an individual, you multiply that number times the accident probability and divide by the 3 to 4 billion people on the Earth.

Mr. DENHAM. Well, the 1,400 also assumes that the accident happens, and the increased risk to an individual takes into account the probability of the accident happening, which, in itself is very small. You would only have the 1,400 fatalities or even the 4 fatalities or the 2 in the phase 1 actually happened.

Mr. NELSON. So you are saying if it happens, but the maximum chance of it happening is 1 in 10 million?

Dr. ENGLEHART. No, the accident probability is approximately 1 in 10,000.

Mr. NELSON. 1 in 10,000.

Mrs. LLOYD. That's all the questions I have at this time.

Mr. NELSON. All right, let me just ask one more.

Do you consider any health effects from other than the radiation dose exposure?

Dr. ENGLEHART. No, sir.

Mr. NELSON. You heard testimony here earlier today that there had been RTG's used on a number of missions, some 20 or so, whatever the number was. So how do these risks as computed here compare? Would it be the same for those other missions in the past that were not on shuttle, or is there a significant difference?

Dr. ENGLEHART. This process, the INSRP process, has been a factor in most of those missions, to my understanding. Similar type of analyses have been done for those missions. I have not reviewed recently what the results of those were. I do know that the calculations for those were done and the results expressed in different ways, so I can't give you a direct answer to that.

Mr. NELSON. We need that, please. Could you send it to us?

[The information follows:]

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The Galileo and Ulysses Missions are the first for which the Interagency Nuclear Safety Review Panel (INSRP) has attempted to quantify potential radiological impact of postulated accidents in terms of calculated health effects. INSRP's Safety Evaluation Reports on radiological impacts for previous missions have been expressed in terms of numbers of people calculated to have lung burdens of plutonium 238 in excess of the occupational limit of 16 nanocuries as a result of the accidents considered. This lung burden, using the earlier dosimetry models, was equivalent to a first year lung dose of 15 rem, and a 50 year dose commitment of 32 rem to the lung, 68 rem to the bone, and 45 rem to the liver. The comparisons between the missions are shown in the following table.

Number of People with Lung Burdens Exceeding the Occupational Limit

Mission	Launch Area Accidents	Reentry Accidents
Galileo	None	None
Ulysses	None	None
Voyager	None	None
Viking	None	0-920
Pioneer	None	0-90
Apollo	0-2000	0-900
SNAP 19/Nimbus	Not quantified	Not quantified

It should be emphasized that the analysis parameters, models, and assumptions for these earlier safety studies differed significantly from the current analyses, and so they are not directly comparable.

James J. Lombardo

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Dr. ENGLEHART. I believe the Department of Energy has those records, and they probably are the better source of that information.

Mr. NELSON. May I request, Madam Chairwoman, of you that we have a request made to the Department of Energy for that comparison?

Mrs. LLOYD. The request will be made. Certainly.

Mr. NELSON. Super. Thanks.

Dr. ENGLEHART. I have been asked by the Department of Energy to put up another Vu-Graph which shows the results of this analysis if one applied the de minimis level of 1 milliem per year, or 50-millrem de minimis dose. Would you be interested in seeing that?

Mrs. LLOYD. Yes.

[The information follows:]

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ADDED RISK TO AN INDIVIDUAL

(CONSIDERING 50 MREM AS DEMINIMUS)

MISSION PHASE	CANCER DEATHS	AVERAGE RISK TO AN INDIVIDUAL
	(GALILEO MISSION)	
0	43.0	1.22 E-08
1	42.6	2.26 E-08
2	0	
3	0	
4	0	
	(ULYSSES MISSION)	
0	41.2	1.18 E-08
1	41.2	2.20 E-08
2	0	
3	0	
4	0	

Note.—Classification cancelled by authority of DOE memorandum from J.J. Lombardo to J. Beadburne, April 15, 1986

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Dr. DUGAN. Is the comparison here, then, between a case where you follow all the various mechanisms for ingestion or whatever versus a case where you compute risk simply on radiation exposure?

Dr. ENGLEHART. Could you say that again?

Dr. DUGAN. If you put this view graph up, will you be giving us numbers that compare a case where you compute risk simply on the basis of radiation exposure versus a case where one goes through the detailed pathways for ingestion?

Dr. ENGLEHART. No, both calculations were done in the same way, considering all radiation dose pathways, inhalation, ingestion of food and inhalation of resuspended material. Both calculations were done on the same basis. The difference between them is that because, especially the worldwide doses are calculated to result in a very very small doses to large numbers of people, and when you apply, then, a health effects conversion factor, you get a large number, that 1,400 number.

If you apply a de miminis level when you say that, gee, below a certain dose level it doesn't make sense to count that.

Dr. DUGAN. So the other case is a zero threshold risk case. This is a minimum threshold.

Dr. ENGLEHART. That's correct.

Dr. DUGAN. All right. Thank you.

Dr. ENGLEHART. That shows that in phases 2, 3, and 4 those doses which resulted in those health effects are below—to any individual are below 1 millirem per year.

Mr. NELSON. And what does it show for zero and one?

Dr. ENGLEHART. For phases 0 and 1, it shows that the results are essentially unaffected; that is, the doses to individuals in the launch area would be higher than that.

Mr. NELSON. Regarding cancer deaths from this kind of exposure.

Dr. ENGLEHART. That's correct.

Mr. NELSON. All right, now why have you got the rest of the slide blocked off?

Dr. ENGLEHART. The rest of the slide shows calculations that are part of a report we are not responsible for, and I understand is not to be yet released.

Mr. NELSON. So out of that we are supposed to understand that you got minimal risk in phases 2, 3, and 4 due to the added risk to an individual considering 50 as the exposure?

Dr. ENGLEHART. Considering 1 millirem per year as being a dose level which is insignificant and should not be included in those calculations.

That level of 1 millirem per year is on the order of 1 percent of natural background.

Mrs. LLOYD. Well, this concludes our hearing. I want to thank you, gentlemen, for your very fine testimony, and I think it is also in order at this time, I'm sorry that I forgot it during the open session, but I do want to thank our staff for the magnificent job that they have done in preparing for the hearings. Some of the staff people even worked over the weekend to have things in order for us. So we want to thank them, and thank all of you who stayed this very late hour.

If there is no further business, then the hearing is adjourned.

[Whereupon, at 7:25 p.m., the subcommittees were adjourned subject to the call of the Chair.]

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APPENDIX

NASA

National Aeronautics and
Space Administration

Washington D.C.
20546

C:MDD:C-19570f

Honorable Don Fuqua
Chairman
Committee on Science and Technology
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

It is requested that the following corrections be included in the hearing record resulting from the March 4, 1986, hearing at which Mr. Silveira testified on the use of RTG's in space missions.

Page	Line(s)	Proposed Wording
64	1497	I think it is in excess of 174 motors that have flown.

I understand that this letter may be inserted in the transcript in the form of an appendix and referred to by footnote in the main text.

Sincerely,

Lynn W. Heninger
Director, Congressional Liaison Division

Enclosure

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Department of Energy
Washington, DC 20585

April 11, 1986

Honorable Marilyn Lloyd
Chairman, Subcommittee on Energy
Research and Production
Committee on Science and Technology
House of Representatives
Washington, D.C. 20515

Dear Madam Chairman:

On March 4, 1986, Lyle C. Wilcox, Deputy Assistant Secretary for Reactor Systems, Development and Technology, appeared before the Science and Technology Subcommittee on Energy Research and Production to discuss use of Radioisotope Thermoelectric Generators in Space Missions.

Following that hearing, you submitted written questions for our response to supplement the record. Enclosed are the answers to those questions, which also have been sent directly to the Committee staff.

If you have any questions, please have your staff call Mike Gilmore or Cathy Hamilton on 252-4277. They will be happy to assist.

Sincerely,

Robert G. Rabben
Assistant General Counsel
for Legislation

Enclosure

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POST-HEARING QUESTIONS AND ANSWERS

RELATING TO THE

MARCH 4, 1986 HEARING

BEFORE THE

HOUSE COMMITTEE ON SCIENCE AND TECHNOLOGY

SUBCOMMITTEE ON ENERGY RESEARCH AND PRODUCTION

WITNESS: DR. LYLE C. WILCOX

DEPUTY ASSISTANT SECRETARY FOR
REACTOR SYSTEMS, DEVELOPMENT AND TECHNOLOGY

U.S. DEPARTMENT OF ENERGY

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QUESTIONS FROM CHAIRMAN MARILYN LLOYD

Question 1: It has been indicated that the Department viewed the environment of the RTG simulant in project Direct Course as being unrealistically severe in comparison to the environment of the RTGs on board the shuttle during an accident situation. What is the basis for this conclusion?

Answer: The Direct Course test has been studied through several independent investigations by DOE contractors, including Fairchild Industries, and most recently by the S-Cubed Division of Maxwell Laboratories, a Los Alamos National Laboratory subcontractor. The conclusion of S-Cubed, based on test data and extensive hydrodynamic code computer calculations, is that:

1. The AN/FO (ammonium nitrate/fuel oil) detonation from DIRECT COURSE provided a more severe airblast environment at the RTG model location than any that could be generated by a LOX/Hydrogen (liquid oxygen/liquid hydrogen) shuttle accident; and, therefore,

2. the DIRECT COURSE result should not be considered in analyzing the potential of the RTG to survive such an accident without scattering radioactive materials.

The basic difference between Direct Course and a liquid hydrogen/liquid oxygen explosion such as is postulated for a space shuttle accident is in the density and velocity of the shock and "debris wave" following the explosion. Combustion

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Answer 1 (continued): products from a liquid oxygen/liquid hydrogen explosion are much less dense than the ammonium nitrate/fuel oil mixture used in Direct Course. Also, the shock wave from the Direct Course explosion was probably traveling at 11,500 ft/sec which was much higher than the velocity of the shock wave from a liquid oxygen/liquid hydrogen explosion. The destructive energy of a shock wave (its dynamic pressure) is proportional to its density and its velocity squared. For a given static pressure (2,000 psi), the dynamic pressure from a liquid hydrogen/liquid oxygen explosion would be 4,800 psi. The dynamic pressure from the Direct Course explosion was estimated to be 15,000 psi. Thus, the destructive energy of the Direct Course shock and debris wave was over three times greater than that which should have been experienced by the simulated RTG. It is this tremendous shock from the debris wave that is thought to have destroyed the RTG and the fuel capsules in Direct Course.

Subsequent tests run in shock tubes with a more controlled and better defined environment (and still more severe than liquid hydrogen/liquid oxygen explosions) have demonstrated that the fuel capsules can withstand the maximum static overpressure (2,000 psi) specified by NASA in the Shuttle Data Book.

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QUESTIONS FROM CHAIRMAN MARILYN LLOYD

Question 2: The analyses revealed that the greatest releases for both the Galileo and the Ulysses would occur during the third phase of the launch. During that period the orbiter maneuvering system is operating and Centaur with the spacecraft is released from the shuttle bay. Please explain for the Committee the significance of this third phase in terms of those releases and in what way they represent a nuclear risk.

Answer: Phase 3 ("Orbit") begins with the first burn of the orbital maneuvering system and ends when the Centaur with spacecraft is deployed from the space shuttle. The Phase 3 safety analysis assumes with some probability that the Centaur can explode. The Phase 3 explosion of the Centaur is assumed to originate in the failure of the common bulkhead that separates the liquid oxygen tank from the liquid hydrogen tank. The propellants are then assumed to mix and explode.

Given an explosion, several scenarios are possible. The explosion overpressure could be great enough to remove the graphite materials used for reentry protection. High velocity fragments (projectiles) could penetrate the containment shell of one or more fuel capsules. Finally, fuel capsules can be driven into the forward bulkhead and other heavy structural members of the space shuttle. For the

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Answer 2 (continued): purposes of the safety analysis, the forward bulkhead (actually a wall with supporting structure, not a bulkhead) was assumed to be made of four inches of solid aluminum with the mechanical properties of concrete. If the fuel capsules hit this wall at a velocity greater than 54 meters per second, their cladding will crack, releasing fuel.

The aforementioned scenarios can lead to the eventual orbital decay (reentry) of unprotected fuel capsules. The analysis assumes the cladding will be burned off upon reentry to the Earth's atmosphere. The fuel could be released over a wide area. However, because the fuel will be so diluted, the risk is minimal. In fact, if the recommendation made separately by the U. S. Nuclear Regulatory Commission that doses below 1 mill'rem per year (the normal background dose is 100-200 millirem per year) be excluded from risk calculations, then the risk from a fuel release in Phase 3 would be essentially zero, and there would be no measurable health effects.

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QUESTIONS FROM CHAIRMAN MARILYN LLOYD

Question 3: Please describe the structural features of the General Purpose Heat Source (GPHS) RTG power systems that specifically describe or define the safety characteristics of the system. In a sequential manner, please describe the physical situation that must exist in order to release the plutonium fuel contained within a GPHS element.

Answer:

- Fuel: The final form chosen for recent missions is plutonium dioxide. It was chosen because the ceramic oxide can readily be hot pressed into pellets that provide a structural base for the remainder of the system. The virtue of plutonium dioxide is that it is essentially insoluble and is not prone to movement up the food chain to humans if a release occurs. It has also been "purified" by an exchange with oxygen-16 to avoid production of neutrons by the interactions of alpha decay products with higher isotopes of oxygen.

- Clad: The fuel is clad with a 22-mil-thick container of iridium, a noble metal in the platinum family. Iridium was selected for the clad material because it is compatible with plutonium dioxide at the design operating temperatures (1,300 degrees Centigrade or 2,372 degrees Fahrenheit operating temperature) and it has a high melting point (2,210 degrees Centigrade or 4,010 degrees Fahrenheit). It is also tough enough to provide impact

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Answer 3
(continued): resistance at high temperatures. Primarily, the clad must provide immobilization of the fuel should it return to Earth. It has sufficient oxidation resistance that it can contain the fuel for years above the ground, completely buried or in sea water.

- o Graphite Impact Shell (GIS): The GIS is a fine-weave pierced fabric (FWPF) graphitic material originally developed for use on missile nosecones. It is a so-called 3-D graphite because it has high density graphite reinforcing fibers in all three directions. It was designed to provide structural support for the fueled clads and to provide impact protection. The structural attachment of the GIS to the aeroshell prevents damage to the graphite insulation between the GIS and the aeroshell. The insulation prevents excessive temperatures on the iridium clad during reentry scenarios.

- o Aeroshell: The aeroshell is the major structural member of the heat source. It is also made of FWPF fiber reinforced graphite. Aside from structural support for the system, its primary purpose is to provide reentry protection for the fueled clads. It is able to

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Answer 3 (continued): survive the thermal shock, temperatures and ablation for all potential reentry environments without approaching a failure point. It also provides some insulation and impact resistance for the fueled clads.

The physical situation that must exist to cause a release of the plutonium fuel is a breaching of the iridium clad. Since the largest calculated releases tend to be associated with postulated explosions of the space shuttle, one way to visualize the physical situation in a sequential manner is to consider each structural feature of the GPHS-RTG.

First, the aluminum outer case of the RTG has to be penetrated or removed. Next the aeroshell and graphite impact shell have to be penetrated or removed. Interpolating from test data the aeroshell and impact shell will be removed by overpressures of 500 psi or greater (for comparison, typical missile silos are designed to withstand an overpressure of 300 psi). Even if the blast pressure does not remove the graphite parts, fragments can penetrate them if the velocity is high enough. For example, tests using small aluminum bullets used to simulate the aluminum fragments expected from a shuttle explosion showed that the cladding could be breached at an impact velocity of 555 meters per second. Typical structural plates hitting the

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Answer 3
(continued): modules flat-on even at very high velocities cause at most minor cracks in the clads. However, plates that impact edge-on (± 5 degrees) can shear the clad and release much of the contained fuel. A test with an aluminum plate driven edge-on into a graphite module at 915 meters per second showed that fuel clads could be sheared.

Once the graphitic parts have been penetrated or removed, the next step would be the penetration or removal of the iridium clad. No explosion overpressure tested (up to 2,200 psi) removed the cladding. High-velocity impacts against hardened targets (such as steel or concrete) can breach the cladding. (The threshold for breaching of an unprotected fuel capsule is 54 meters per second against steel and 65 meters per second against concrete. There were no impact failures in tests against sand at velocities up to 250 meters per second, which was the maximum velocity achievable in the impact facility.)

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QUESTIONS FROM CHAIRMAN MARILYN LLOYD

Question 4: The safety analysis applied to the RTG is, according to the FSAR, based upon accident, mission and environmental conditions provided by NASA in the Shuttle Data Book entitled, "Space Shuttle Data for Planetary Mission Radioisotope Thermoelectric Generator (RTG) Safety Analysis." What sort of quantitative information is provided in this data book, and how is it applicable to the Department's safety analysis? Also, your analysis is based upon the safety test programs conducted by the Los Alamos National Laboratory according to the FSAR Volume II. How are these two sources of information combined or integrated to form the data base necessary to perform the probability risk analyses?

Answer: The NASA document "Space Shuttle Data for Planetary Mission Radioisotope Thermoelectric Generator (RTG) Safety Analysis," which is referred to as the Shuttle Data Book, contains descriptions of the space shuttle and Centaur, the two spacecraft (Galileo and Ulysses), the launch site, launch safety, accidents and assorted accident environments and probabilities. Much of this information is relevant to the safety analysis report which must use the accident-related information to calculate the response of the fuel capsules to such postulated accidents.

The Shuttle Data Book includes such specific quantitative information as explosion overpressures, fragments (projectiles), fireballs, explosive failure mode failure probabilities, reentry conditions, overall launch vehicle response mode and failure probabilities.

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Answer 4 (continued): In order to analyze the response of the fuel capsules to the accident environments given in the Shuttle Data Book, it is necessary to have test data. The Department's Los Alamos National Laboratory ran a series of safety tests that encompassed explosions, impacts, fires, projectiles and flyer plates (a flat-on projectile). These tests helped define the response of the fuel capsules to the environments given in the Shuttle Data Book.

In summary, the Shuttle Data Book and the Los Alamos tests complement each other and are integral parts of the safety analysis reports. The Shuttle Data Book, in effect, provides the accident conditions to be considered in the safety analyses and tests, and the tests themselves provide the information on the response of the fuel capsules to those accidents. The final integration of these two sources of information is in the Final Safety Analysis Report.

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QUESTIONS FROM CHAIRMAN MARILYN LLOYD

Question 5: Returning to the adequacy of the data base utilized to calculate nuclear risk associated with RTG flights on board the shuttle spacecraft, are there any additional testing activities that should be undertaken during the hiatus we apparently will have before an actual Galileo flight can be launched? Such tests would significantly expand our knowledge about potential accidents and thereby improve our statistical calculations as they relate to the risk associated with flying these RTG systems.

Answer: There are tests which would expand our knowledge about potential accidents. The Final Safety Analysis Report (FSAR) indicates that the close-in effects of exploding liquid hydrogen/liquid oxygen (pressures, impulses, fragments, thermal) are the principal contributors to the calculated release and dispersion of fuel. The data used to estimate the close-in effects were taken from explosion tests run for other purposes. As a result, conservative assumptions have been used to account for uncertainties. Thus, tests to better define the near-field explosion environment would appear useful.

Related to these tests on fundamental explosion phenomenology would be a test involving a replication of the forward bulkhead of the space shuttle. Such a test could determine better the response of fuel capsules that are postulated to be explosively driven into the forward bulkhead. (This was a

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Answer 5 (continued): major contributor to the fuel releases as calculated in the FSAR).

As additional information concerning potential space shuttle accident environments becomes available, the DOE will consider the need for such additional tests before the next shuttle is launched with a nuclear power source. The scope, funding requirements, potential findings and benefits, and other factors are being reviewed to determine which, if any, additional tests should be conducted.

It is possible that with better definition of accident environments, the source terms estimated for analysis would be reduced significantly.

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QUESTIONS FROM CHAIRMAN MARILYN LLOYD

Question 6: An explosion working group was formed by the Department in order to evaluate the conditions under which this experiment occurred. What was the finding of this group and what was the subsequent conclusions of the independent review committees evaluation?

Answer: The Explosion Working Group was set up by DOE to investigate the Direct Course test, postulated space shuttle explosions, and future safety tests. The Explosion Working Group consisted of 14 outside experts and 11 outside contributors. The Explosion Working Group spent about six months studying various issues and released a draft report in 1984 and a final report on July 8, 1985. The title of this report is "Report of Space Transportation System (STS) Explosion Working Group for Department of Energy." In this final report the Explosion Working Group concluded that the "Direct Course results should not be used to assess the fuel containment capabilities of the RTG in postulated launch abort scenarios." They supported this conclusion by comparing the close-in effects of Direct Course versus liquid hydrogen/liquid oxygen and finding that the former was much more severe than the latter. Also, there are uncertainties on the actual close-in explosion environment in Direct Course.

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Answer 6 (continued): In June 1984 NASA established a Management Review Panel to review the existing data relative to the safety of shuttle RTG missions, including a review of Direct Course. On February 5, 1985, this Panel issued a "Report of the NASA Management Review Panel on the Safety of Shuttle RTG Missions." As one of its findings, the Panel stated: "The 'Direct Course test' did not provide the specific information on RTG survival capability that it was intended to provide, but it did provide information that could prove useful in future tests and analyses of RTG structural limits." The Department modified its subsequent test program to include information learned from Direct Course. The Panel also found that "the reaction products trailing the initial shock in the Direct Course test provided a more severe secondary environment to the RTG mockup than would the products of a liquid hydrogen/liquid oxygen explosion. (In this finding, we are in agreement with the Explosion Working Group.)" This is consistent with analyses and tests by other organizations.

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QUESTIONS FROM CHAIRMAN MARILYN LLOYD

Question 7: What were the physical conditions experienced by the RTG simulant during the explosive period?

Answer: The actual physical conditions in the Direct Course explosion are unknown because of failures of the pressure sensors at the RTG location. Post-test calculations indicate that the static overpressure* could have been as high as 1,800 pounds per square inch (psi). The RTG was located close enough to the explosive that it was also blasted by a "debris wave" of material (explosion products, casing material, etc.). This "debris wave" produced a secondary shock or dynamic pressure** calculated to be 10,000 to 15,000 psi. Based on several studies, it has been concluded that this "debris wave" destroyed the simulated RTG.

---

* In an explosion, a blast wave moves outward from the center of the explosion. One of the important characteristics of the blast wave is the overpressure, which is the pressure above normal atmospheric pressure. One term used to characterize this blast wave is the static pressure which is the peak overpressure at the point of interest.

** Associated with the explosion is a blast wind, which produces a dynamic pressure. The dynamic pressure is proportional to the square of the wind velocity and to the density of the gas behind the shock front. The static pressure and the dynamic pressure are physically related and are a function of the explosive source in the near field.

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QUESTIONS FROM CHAIRMAN MARILYN LLOYD

Question 8: Were any modifications or changes to the RTG design incorporated subsequent to this experiment?

Answer: In view of the independent studies which said that the Direct Course test was not representative of a liquid hydrogen/liquid oxygen explosion, no changes were made in the design. Instead, a series of explosion tests under more controlled conditions were run in which the dynamic pressure associated with the explosion products was calculated to be reduced to approach the dynamic pressure of a postulated shuttle explosion (although these were still more severe.) These tests show that the fuel capsules could withstand 2,200 pounds per square inch static overpressure. Separate tests defined the failure threshold for projectiles and impacts.

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COMMITTEE ON SCIENCE AND TECHNOLOGY
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WASHINGTON, DC 20515
(202) 225-6371

March 19, 1986

Dr. Lyle C. Wilcox
Deputy Assistant Secretary for
Reactor Systems, Development and Technology
Department of Energy
Washington, D. C. 20585

Dear Dr. Wilcox:

I would like to thank you for your testimony at our March 4, 1986 hearing on the Use of RTG's in Space Missions. I am enclosing additional questions that we were unable to ask you at the time of the hearing, but which we would like to have included for the record. Please submit your response on or before April 4, 1986.

Should you have any questions regarding this matter please contact Mr. Nelson Milder (202/225-5378) of my staff.

Sincerely,

MARILYN LLOYD, Chairman
Subcommittee on Energy
Research and Production

ML:Nms
Enclosure

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QUESTIONS FOR DOE

- IT HAS BEEN INDICATED THAT THE DEPARTMENT VIEWED THE ENVIRONMENT OF THE RTG SIMULANT IN PROJECT DIRECT COURSE AS BEING UNREALISTICALLY SEVERE IN COMPARISON TO THE ENVIRONMENT OF THE RTG'S ON BOARD THE SHUTTLE DURING AN ACCIDENT SITUATION. WHAT IS THE BASIS FOR THIS CONCLUSION?

- THE ANALYSES REVEALED THAT THE GREATEST RELEASES FOR BOTH THE GALILEO AND THE ULYSSES WOULD OCCUR DURING THE THIRD PHASE OF THE LAUNCH. DURING THAT PERIOD THE ORBITER MANEUVERING SYSTEM IS OPERATING AND CENTAUR WITH THE SPACECRAFT IS RELEASED FROM THE SHUTTLE BAY. PLEASE EXPLAIN FOR THE COMMITTEE THE SIGNIFICANCE OF THIS THIRD PHASE IN TERMS OF THESE RELEASES AND IN WHAT WAY THEY REPRESENT A NUCLEAR RISK.

- PLEASE DESCRIBE THE STRUCTURAL FEATURES OF THE GENERAL PURPOSE HEAT SOURCE (GPHS) - RTG POWER SYSTEMS THAT SPECIFICALLY DESCRIBE OR DEFINE THE SAFETY CHARACTERISTICS OF THE SYSTEM. IN A SEQUENTIAL MANNER, PLEASE DESCRIBE THE PHYSICAL SITUATION THAT MUST EXIST IN ORDER TO RELEASE THE PLUTONIUM FUEL CONTAINED WITHIN A GPHS ELEMENT.

- THE SAFETY ANALYSIS APPLIED TO THE RTG IS, ACCORDING TO THE FSAR, BASED UPON ACCIDENT, MISSION AND ENVIRONMENTAL CONDITIONS PROVIDED BY NASA IN THE SHUTTLE DATA BOOK ENTITLED, "SPACE SHUTTLE DATA FOR PLANETARY MISSION RADIOISOTOPE THERMOELECTRIC GENERATOR (RTG) SAFETY ANALYSIS." WHAT SORT OF QUANTITATIVE INFORMATION IS PROVIDED IN THIS DATA BOOK, AND HOW IS IT APPLICABLE TO THE DEPARTMENT'S SAFETY ANALYSIS? ALSO, YOUR ANALYSIS IS BASED UPON THE SAFETY TEST PROGRAMS CONDUCTED BY THE LOS ALAMOS NATIONAL LABORATORY ACCORDING TO THE FSAR VOLUME II. HOW ARE THESE TWO SOURCES OF INFORMATION COMBINED OR INTEGRATED TO FORM THE DATA BASE NECESSARY TO PERFORM THE PROBABILITY RISK ANALYSES?

- RETURNING TO THE ADEQUACY OF THE DATA BASE UTILIZED TO CALCULATE NUCLEAR RISK ASSOCIATED WITH RTG FLIGHTS ON BOARD THE SHUTTLE SPACECRAFT, ARE THERE ANY ADDITIONAL TESTING ACTIVITIES THAT SHOULD BE UNDERTAKEN DURING THE HIATUS WE APPARENTLY WILL HAVE BEFORE AN ACTUAL BALILEO FLIGHT CAN BE LAUNCHED. SUCH TESTS WOULD SIGNIFICANTLY EXPAND OUR KNOWLEDGE ABOUT POTENTIAL ACCIDENTS AND THEREBY IMPROVE OUR STATISTICAL CALCULATIONS AS THEY RELATE TO THE RISK ASSOCIATED WITH FLYING THESE RTG SYSTEMS?

QUESTIONS FOR DOE ON PROJECT DIRECT COURSE

- AN EXPLOSION WORKING GROUP WAS FORMED BY THE DEPARTMENT IN ORDER TO EVALUATE THE CONDITIONS UNDER WHICH THIS EXPERIMENT OCCURRED. WHAT WAS THE FINDING OF THIS GROUP AND WHAT WAS THE SUBSEQUENT CONCLUSIONS OF THE INDEPENDENT REVIEW COMMITTEES EVALUATION?

- WHAT WERE THE PHYSICAL CONDITIONS EXPERIENCED BY THE RTG SIMULANT DURING THE EXPLOSIVE PERIOD?

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- WERE ANY MODIFICATIONS OR CHANGES TO THE RTG DESIGN INCORPORATED SUBSEQUENT TO THIS EXPERIMENT?

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[illegible], Florida, CHAIRMAN

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Executive Director
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General Counsel
JOYCE GROSS FRENWALD
Republican Staff Director

March 19, 1986

Dr. Milton A. Silveira
Chief Engineer
National Aeronautics and Space Administration
Washington, D. C. 20546

Dear Dr. Silveira:

I would like to thank you for your testimony at our March 4, 1986 hearing on the Use of RTG's in Space Missions. I am enclosing additional questions that we were unable to ask you at the time of the hearing, but which we would like to have included for the record. Please submit your response on or before April 4, 1986.

Should you have any questions regarding this matter please contact Mr. Nelson Milder (202/225-5378) of my staff.

Sincerely,

MARILYN LLOYD, Chairman
Subcommittee on Energy
Research and Production

ML:Hms
Enclosure

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QUESTIONS FOR NASA

- PLEASE DESCRIBE FOR THE COMMITTEE THE EVENTS THAT LED UP TO THE CONVENING OF A NASA MANAGEMENT REVIEW PANEL UNDER THE DIRECTION OF DR. COHEN OF JSC EARLY IN 1984 TO REVIEW THIS ENTIRE MATTER. WHAT PROCEDURES WERE USED BY THIS PANEL TO ASSESS THE CONTENTS OF THE SHUTTLE DATA BOOK AS RELATED TO THE RTG QUESTION. WHAT WAS THE OUTCOME OF THIS PANEL'S FINDINGS? HOW DID NASA INCORPORATE THESE FINDINGS INTO THE INFORMATION PROVIDED TO THE DEPARTMENT OF ENERGY ON PROBABILITIES ASSOCIATED WITH VARIOUS FAILURE MODES?

- WHAT PROCEDURES WERE USED IN RECALCULATING PROBABILITY VALUES? WAS THE DEPARTMENT INVOLVED IN ANY OF THESE DISCUSSIONS REGARDING CHANGES IN THE SHUTTLE DATA BOOK INFORMATION?

- IN THE SHUTTLE DATA BOOK (JSC-08116), PARAGRAPH 3.0, ENTITLED "ACCIDENTS" PROVIDES AN EXPLANATION OF NASA'S RATIONALE FOR REJECTING PROBABALISTIC METHODOLOGIES IN THE DESIGN OF THE SHUTTLE. COULD YOU REVIEW, FOR THE COMMITTEES, THE ARGUMENTS CONTAINED THEREIN, DESCRIBING NASA'S VIEW ON THE SHORTCOMINGS OF SUCH TECHNIQUES AS THEY RELATE TO VALIDATING THE SHUTTLE'S SAFETY AND RELIABILITY FEATURES?

- THE MANAGEMENT METHODOLOGIES DESCRIBED IN PARAGRAPH 3.1 OF THIS DOCUMENT DETAIL THE ACCEPTED PROCEDURES USED BY NASA. PLEASE EXPLAIN THE RATIONALE FOR NASA'S PLACING MORE CREDENCE IN THESE PROCEDURES AS OPPOSED TO PROBABALISTIC METHODOLOGIES.

- ACCORDING TO THE FINAL SAFETY ANALYSIS REPORT (FSAR), NASA HAS IDENTIFIED A LIMITED NUMBER OF CHARACTERISTIC EXPLOSIONS THAT COULD AFFECT THE INTEGRITY OF THE RTG STRUCTURE. COULD YOU DEFINE THESE EXPLOSION TYPES FOR THE COMMITTEE AND EXPLAIN THEIR SIGNIFICANCE AS THEY RELATE TO THE RTG? ALSO, DISCUSS THE SIGNIFICANCE OF THE PROJECT PYRO EXPERIMENTS AS THEY RELATE TO THESE ANALYSES.

- HISTORICALLY, WHAT HAS BEEN THE FLIGHT RELIABILITY OF UNMANNED EXPENDABLE LAUNCH VEHICLES (ELV'S)?

- HOW DO THESE FIGURES COMPARE WITH THE EXPECTED RELIABILITY OF THE SPACE SHUTTLE?

- WHY IS THE SPACE SHUTTLE EXPECTED TO HAVE SUCH A GREATER LEVEL OF RELIABILITY THAN ELV'S?

- WHY DOES NASA BELIEVE THAT IT IS MORE APPROPRIATE TO USE "ENGINEERING JUDGMENT" RATHER THAN "NUMERICAL PROBABILITY" TO ENSURE THE FLIGHT SAFETY OF THE SPACE SHUTTLE?

- HOW MUCH TESTING WOULD BE REQUIRED TO DEMONSTRATE SRB NUMERICAL RELIABILITIES TO 1 IN 10,000?

- WHY CAN'T WE APPLY WELL ESTABLISHED AIRCRAFT CERTIFICATION METHODOLOGY TO SHUTTLE RELIABILITY ASSURANCE?

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QUESTION D-1:

Please describe for the committee the events that led up to the convening of a NASA management review panel under the direction of Dr. Cohen of JSC early in 1984 to review this entire matter. What procedures were used by this panel to assess the contents of the Shuttle Data Book as related to the RTG question. What was the outcome of this panel's findings? How did NASA incorporate these findings into the information provided to the Department of Energy on probabilities associated with various failure modes?

ANSWER D-1:

The panel under Dr. Cohen was appointed to develop the data which was published in the Shuttle Data Book. This was done when it was discovered that the data being used by the Department of Energy was not developed or approved by the Shuttle Program. The data which was placed under control of the Shuttle Program Change Control Board was published in the Shuttle Data Book (JSC-08116) which is the official submission of data to the Department of Energy for use in development of the necesary analysis in the approval of space flight of Radioactive Thermoelectric Generators.

QUESTION D-2:

What procedures were used in recalculating probability values? Was the department involved in any of these discussions regarding changes in the Shuttle Data Book information?

ANSWER D-2:

The probabilities in the Shuttle Data Book were developed specifically for the Department of Energy analysis as best estimates by the responsible technical managers and reviewed by the Cohen panel and Space Shuttle management.

QUESTION D-3

In the Shuttle Data Book (JSC-08116), paragraph 3.0, entitled "accidents" provides an explanation of NASA's rationale for rejecting probabalistic methodologies in the design of the shuttle. Could you review, for the committees, the arguments contained therein, describing NASA's view on the shortcomings of such techniques as they relate to validating the shuttle's safety and reliability features?

ANSWER D-3:

Because of a limited data base statistical methods are not used. The failure rates of hardware usually are obtained during development and extended experience with the final design is not available. When a failure is encountered a redesign is usually initiated, thus eliminating the experience base to that point in time. The inspection and testing of hardware between flights also bias the data which makes a mathematical statistical analysis not applicable. Technical evaluation is considered better than using a false sense of confidence which sometimes can be obtained from a probability analysis.

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QUESTION D-4:

The management methodologies described in paragraph 3.1 of this document detail the accepted procedures used by NASA. Please explain the rationale for NASA's placing more credence in these procedures as opposed to probabalistic methodologies.

ANSWER D-4:

NASA experience in the Apollo, Apollo-Soyuz, Skylab and Shuttle programs indicates detail technical review of hardware performance is more valuable than a statistical analysis which can be mathematically manipulated.

QUESTION D-5:

According to the Final Safety Analysis Report (FSAR), NASA has identified a limited number of characteristic explosions that could affect the integrity of the RTG structure. Could you define these explosion types for the committee and explain their significance as they relate to the RTG? Also, discuss the significance of the project pyro experiments as they relate to these analyses.

ANSWER D-5:

In virtually all the scenarios, it is postulated that the initial failure would propagate to the Centaur stage, which would then explode within the cargo bay of the orbiter (an External Tank could also cause overpressure). Explosion environments from a Centaur or External Tank explosion were then defined. Based on the near field test data points from Project Pyro, overpressure and impulse environments were developed using a zone approach. Overpressure and impulse were plotted versus the percentage of time that pressure would be expected to exceed a particular value. There are basically two types of explosions that could occur: (1) a "confined-by-missile" explosion in which the event would occur with the confines of the Centaur, and (2) an event that would lead to spill of the propellants and mixing at various distances from the RTG resulting in explosion. The threat to the RTG is then defined based upon the number of tank diameters away from the RTG.

Project Pyro represents the only large body of close-in experimental data from the liquid hydrogen/liquid oxygen explosions using quantities greater than laboratory amounts. It represents the best data we have to define the expected results of a near field liquid hydrogen/liquid oxygen explosion.

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QUESTION D-6:

Historically, what has been the flight reliability of unmanned expendable launch vehicles (ELV's)?

ANSWER D-6:

	Flights	Failures
Scout	106	14
Delta	177	12
Atlas Centaur	65	9
Atlas E and F	80	8
Titan A and C	40	9
Titan D	22	0
Titan B	67	1
Titan E	7	0
Titan 34D	8	1

QUESTION D-7:

How do these figures compare with the expected reliability of the Space Shuttle?

ANSWER D-7:

It is NASA's intent to make the Space Shuttle more reliable than ELV's.

QUESTION D-8:

Why is the Space Shuttle expected to have such a greater level of reliability than ELV's?

ANSWER D-8:

The Space Shuttle being a more recent design which uses the available new technology to provide better designed, tested and analyzed hardware, uses additional redundancy to obtain higher reliability.

QUESTION D-9:

Why does NASA believe that it is more appropriate to use "engineering judgment" rather than "numerical probability" to ensure the flight safety of the Space Shuttle?

ANSWER D-9:

Sufficient data base does not exist to use numerical probabilities.

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QUESTION D-10:

How much testing would be required to demonstrate SRB numerical reliabilities to 1 in 10,000?

ANSWER D-10:

If 10,000 successful tests were performed, this would statistically indicate the probability of three failures in 10,000 events with a 95% confidence. If 100,000 successful tests were performed, this would statistically indicate the probability of three failures in 100,000 events with a 96% confidence.

QUESTION D-11:

Why can't we apply well established aircraft certification methodology to Shuttle reliability assurance?

ANSWER D-11:

The Space Shuttle program uses a very detailed certification program for both hardware and software which we believe is more extensive than an aircraft certification methodology.

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DON FUQUA, Florida, Chairman

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Executive Director
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General Counsel
JOYCE GROSS MCDONALD
Republican Staff Director

March 19, 1986

Mr. Leven B. Gray
Manager for Nuclear Safety
HQ NASA Safety Office
Washington, D. C. 20546

Dear Mr. Gray:

I would like to thank you for your testimony at our March 4, 1986 hearing on the Use of RTG's in Space Missions. I am enclosing additional questions that we were unable to ask you at the time of the hearing, but which we would like to have included for the record. Please submit your response on or before April 4, 1986.

Should you have any questions regarding this matter please contact Mr. Nelson Milder (202/225-6378) of my staff.

Sincerely,

Marilyn Lloyd

MARILYN LLOYD, Chairman
Subcommittee on Energy
Research and Production

ML:Nms
Enclosure

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QUESTIONS FOR INSRP

- IT IS OUR UNDERSTANDING THAT NASA'S NORMAL PROCEDURES DO NOT INVOLVE ASSIGNING PROBABILITIES TO VARIOUS FAILURE MODES ASSOCIATED WITH A POTENTIAL SHUTTLE ACCIDENT. RATHER, THEY USE ENGINEERING JUDGMENT TO ESTIMATE WHETHER A PARTICULAR COMPONENT OR ELEMENT OF THE SHUTTLE SPACECRAFT WILL FAIL UNDER VARIOUS ENVIRONMENTS AND OPERATING CONDITIONS. IS THERE SUFFICIENT INFORMATION IN THE DATA BASE TO MAKE A MEANINGFUL PROBABILITY ASSESSMENT?

- COULD YOU PLEASE DESCRIBE THE MEMBERSHIP OF THE FIVE SUBPANELS TO INSRP UPON WHICH YOU DEPEND FOR INDEPENDENT ANALYSES OF THE SAFETY ANALYSIS REPORT?

- BASED UPON YOUR ANALYSES TO DATE, DO YOU SEE ANY BASIS FOR THE CONCERN THAT AS A RESULT OF THE CHALLENGER ACCIDENT THE RTG'S SHOULD NOT BE FLOWN ON BOARD THE SHUTTLE?

- RETURNING TO THE ADEQUACY OF THE DATA BASE UTILIZED TO CALCULATE NUCLEAR RISK ASSOCIATED WITH RTG FLIGHTS ON BOARD THE SHUTTLE SPACECRAFT, ARE THERE ANY ADDITIONAL TESTING ACTIVITIES THAT SHOULD BE UNDERTAKEN DURING THE HIATUS WE APPARENTLY WILL HAVE BEFORE AN ACTUAL GALILEO FLIGHT CAN BE LAUNCHED. SUCH TESTS WOULD SIGNIFICANTLY EXPAND OUR KNOWLEDGE ABOUT POTENTIAL ACCIDENTS AND THEREBY IMPROVE OUR STATISTICAL CALCULATIONS AS THEY RELATE TO THE RISK ASSOCIATED WITH FLYING THESE RTG SYSTEMS?

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NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

APR 07 RECD

Reply to Attn of C:NED:C-185731

APR 3 1986

Honorable Marilyn Lloyd
Chairman
Subcommittee on Energy
Research and Production
Committee on Science
and Technology
House of Representatives
Washington, DC 20515

Dear Madam Chairwoman:

Enclosed are responses to written questions submitted by your letter of March 19, 1986, resulting from the hearing held on March 4 at which Mr. Gray testified on the use of RTG's in space missions.

Sincerely,

Lynn M. Heninger
Director, Congressional Liaison Division

Enclosure

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DURING THE MARCH 4, 1986, HEARING AT WHICH MR. GRAY TESTIFIED ON THE USE OF RTG'S IN SPACE MISSIONS.

QUESTION D-1:

It is our understanding that NASA's normal procedures do not involve assigning probabilities to various failure modes associated with a potential shuttle accident. Rather, they use engineering judgment to estimate whether a particular component or element of the shuttle spacecraft will fail under various environments and operating conditions. Is there sufficient information in the data base to make a meaningful probability assessment?

ANSWER D-1:

Determining the real failure rate for any complex aerospace system such as the Space Shuttle is difficult. To demonstrate even a reliability of .999 with 50 percent confidence requires over 500 tests, and to provide the same reliability with 90 percent confidence requires several thousand tests. Obviously, the real failure rates for different shuttle systems cannot be established from only 25 flights with any degree of confidence. On the other hand, the use of applicable past history and the shuttle experience to date does provide better confidence than the use of engineering judgment by itself. There are statistical and engineering means to factor in human error and to utilize past history and the Shuttle's own experience. This should provide the best available estimate of reliability or conversely failure rates, certainly significantly better than pure engineering judgment. The tight controls on the failure analysis and corrective action process require that fixes be instituted to prevent recurrences of failures as quickly as possible (usually before the next flight). This means that the failure rates are changing with each flight. This adds to the difficulty in making a probability assessment.

QUESTION D-2:

Could you please describe the membership of the five subpanels to INSRP upon which you depend for independent analyses of the Safety Analysis Report?

ANSWER D-2:

The members and their organizational affiliations are shown below:

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GALILEO/ULYSSES INSRP

NAME	AGENCY/CONTRACTING AGENCY	ORGANIZATION
Coordinators		
Gray, Leven B.	NASA	NASA HQS/DS
Joyce, COL John P.	DOD	AFISC/SND
Klug, Norman P.	DOE	DOE HQS/EH-33
Launch Abort Subpanel		
Brown, Robert W.	NASA	JSC/FM
Fletcher, Robert F.	NASA	JSC/MP
Gerron, Robert	NASA	KSC/SF-ENG
Marshall, John W.	DOD	AFRPL/LKLH
Parker, Loyd C.	DOD	RTI
Reynolds, Joel R.	NASA	KSC/SF-SAF
Rice, LTC John W.	DOD	AFISC/SNA
Riehl, William A.	NASA	MSFC/EH-31
Seabourn, C. Mel	DOE	LANL/Q-6
Ullian, Louis J. (Chairman)	DOD	ESMC/SEM
Reentry Subpanel		
Ailor, Dr. William H.	DOD	Aerospace Corp
Blaylock, LT Donal L.	DOD	AFWL/AWYS
Hagan, James C.	DOE	JHU/APL
Jaffe, Peter	NASA	JPL/67-201
McRonald, Dr. Angus D.	NASA	JPL/157-102
Sutton, Dr. Kenneth (Chairman)	NASA	LaRC/366
Meteorology Subpanel		
Anderson, Dr. Jeffrey	NASA	MSFC/ED-44
Boyd, Billie F.	DOD	ESMC/NER
Key, CPT Larry	DOD	AFESC/RDVS
Kurzeja, Dr. Robert J. (Chairman)	DOE	SRL
Meyers, MAJ Tom	DOD	ESMC/NER
White, LT Bruce	DOD	AFWL/AWYS
Biomedical and Environmental Effects Subpanel		
Cuddihy Jr., Richard G.	DOE	ITRI
Goldman, Dr. Marvin (Chairman)	DOE	U. of Cal.
Marmaro, George M.	NASA	KSC/MD-ENV
Nelson, LTC Robert C.	DOD	AFISC/SNAR
Park, Dr. James F.	DOE	BNL
Pinder III, Dr. John E.	DOE	SREL

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Beasley, Dr. Thomas M.		Oregon St. U.
Cutshall, Dr. Norman	DOE	ORNL
Hayes, Dr. David W.	DOE	SRL
Noskin, Dr. Victor E.	DOE	LLNL
Osterberg, Dr. Charles L. (Chairman)	DOE	DOE HQS/ER-75

Consultants

Schaefer, George	NASA	LeRC
Vedder, John D.	NASA	MDTSCO

As noted, the three Coordinators are supported by five subpanels, each with a chairperson. The membership of the subpanels is primarily determined by the subpanel chairman who selects personnel with the necessary technical expertise to do that subpanel's portion of the evaluation and to achieve a mix of persons from the three agencies as well as academia and industrial concerns. The necessity for independent judgment is continually stressed to the subpanels and we continue to encourage members who do not feel that they can fulfill this requirement to divorce themselves from the decision-making process on that issue or to step down entirely. Over the history of the INSRP, this has occurred on several occasions. The subpanels have a mix of personnel to assure that domination by one group or organization is not possible, and to assure members are selected who have no specific vested interest in the portion of the program being evaluated.

QUESTION D-3:

Based upon your analyses to date, do you see any basis for the concern that as a result of the Challenger accident, the RTG's should not be flown on board the shuttle?

ANSWER D-3:

As stated in our testimony during the hearings on March 4, 1986, "It is the INSRP's position that we must review the results of the ongoing accident investigation before we can make any final nuclear risk assessment for Galileo and Ulysses." It should also be clearly stated that INSRP does not make recommendations for or against launching a specific mission, but rather tries to provide the best technically correct data base possible describing the events, environments, consequences, health risks, and comparative risk information on which the decision-maker can in part base his decision. Since the ultimate decision is a risk versus benefit decision, and we do not

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environment, we cannot provide a sound decision and do not attempt to.

QUESTION D-4:

Returning to the adequacy of the data base utilized to calculate nuclear risk associated with RTG flights on board the shuttle spacecraft, are there any additional testing activities that should be undertaken during the hiatus we apparently will have before an actual Galileo flight can be launched? Such test would significantly expand our knowledge about potential accidents and thereby improve our statistical calculation as they relate to the risk associated with flying these RTG systems.

ANSWER D-4:

There are major technical areas in which better data would improve the evaluation and eliminate the need for current conservatism. These include the following:

a. An Understanding of the Near Field Blast Phenomena Associated with LOX/LH_2 Explosions - The energy output from an LOX/LH_2 explosion is directly related to the characteristics of the fuel/oxidizer mixture. There has been very little work done to investigate this phenomena. The test program required must include laboratory tests and math models derived from the laboratory work. These could then be used to develop and conduct subscale explosive tests to verify the models.

   A better understanding of tank rupture energy release in space vacuum is also needed (i.e., is it equivalent to an explosion).

b. Effect of a Centaur LOX Hydrogen Explosion and its Consequences from Orbiter Bay Confinement - The orbiter bay would tend to confine and influence the LOX hydrogen mixing from Centaur tank failures. It also would tend to channel any explosion products and the blast wave. This could significantly change the characteristics of the blast wave as it impinges on the RTG's and may have significant consequences regarding RTG break-up. An investigation into this question could include analytical modeling and scale model tests, and would also enhance the evaluation by providing better information.

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SPACE SYSTEMS DIVISION
GENERAL ELECTRIC COMPANY • VALLEY FORGE SPACE CENTER • PO BOX 8555 • PHILADELPHIA, PENNSYLVANIA 19101 • (215) 354-1000

April 2, 1986

Honorable Marilyn Lloyd, Chairman
Subcommittee on Energy Research and Production
House Committee on Science and Technology
Suite 2321 Rayburn House Office Building
Washington, DC 20515

Dear Madam Chairman:

Your letter of March 19, 1986 transmitted additional questions relating to my testimony at the March 4 hearing on the Use of RTGs in Space Missions. I am pleased to enclose answers to these additional questions as an attachment to this letter.

Should you require additional information or further clarification, please contact my office directly, or Bill Patterson, of GE's Washington Office, at your preference.

Thank you for this further opportunity to support your timely evaluation concerning the use of isotope electric power generators in space.

Sincerely,

Giles Sinkewiz
General Manager
Spacecraft Operations

GS/mn
Enclosure
cc: W. Patterson, GE

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QUESTIONS AND RESPONSES

QUESTION: In a December 20, 1985 letter to the Department of Energy, the General Electric Company did what appeared to be a recalculation of the expected radiological material release assuming higher values for the SRB accident probability. In essence, they increased the probability for such accidents by two orders of magnitude. According to their documents, the results of their calculations suggest that the radiological releases would not be significantly altered by such an increase in probability of failure for the SRB. Could you elaborate on this for the committee?

RESPONSE: The Inter-Agency Nuclear Safety Review Panel (INSRP) believed that the SRB failure probability should be higher than that estimated by NASA and contained in the Shuttle Data Handbook. GE performed an analysis at DOE's request to determine the effect of the higher probability on the predicted release expectations, i.e., the probability weighted release predictions.

Since the accident scenarios and environments were unchanged from those utilized in the FSAR, the predicted fuel releases for each type of SRB accident did not change. Only the probability of having that type of accident increased.

SRB failures, as categorized by NASA and analyzed in the FSAR, fall into two generic accident scenarios.

1) Left SRB failures which occur during the first two seconds of flight which could result in collision with the service tower. This was estimated by NASA to result in a Centaur explosion with a static overpressure of 2000 psi.

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2) All other SRB failures would result in loss of vehicle guidance control and necessitate range safety destruct action. This was placed by NASA in a category of failures which could result in a Centaur explosion centered within one Centaur tank diameter (14 feet) of the RTGs. A probabilistic prediction of static overpressure was defined by NASA for this class of potential accidents, frequently referred to as 1D failure mode.

The above two generic scenarios involving SRB failures are specified to occur only in mission Phase 1, First Stage Ascent. Using the predicted releases and probabilities for all release events in mission Phase 1, release expectations for the first phase were calculated using the following general equation:

$$\text{Expectation, } Q_{PH} = \frac{\sum Q_i P_i}{P_{PH}}$$

Where Q_{PH} = Phase release expectation.

$Q_i P_i$ = Product of all source terms for the phase and their associated probabilities of occurrence.

P_{PH} = The total probability of any accident failure in the mission phase.

The resulting release expectations using the Shuttle Data Handbook accident probabilities are shown in Table 1.

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TABLE 1

Release Expectations for Phase 1 Using Shuttle Data Book Probabilities

	PHASE TOTAL	LEFT SRB	ALL OTHER SRB	CENTAUR SPILL MODE	CENTAUR TANK FAILURE	EXTERNAL TANK FAILURE
Release Expectation	3650	245	1304	1497	153	451
Failure Probability	5.31E-5	4.0E-7	9.5E-6	3.65E-5	5.0E-6	1.7E-6

The individual source terms and their associated probabilities of occurrence for the above are shown in the FSAR Supplement to Volume II (Book 1) Accident Model Document, GESP-7200, 17 December 1985, page B-1, items 21 through 88.

Similarly, for the same accidents and predicted releases and utilizing the SRB failure probabilities estimated by INSRP, the release expectations as shown in Table 2 were determined.

TABLE 2

Release Expectations for Phase 1 Using INSRP SRB Failure Probabilities

	PHASE TOTAL	LEFT SRB	ALL OTHER SRB	CENTAUR SPILL MODE	CENTAUR TANK FAILURE	EXTERNAL TANK FAILURE
Release Expectation	7726	780	6856	64	7	19
Failure Probability	1.24E-3	2.98E-5	1.17E-3	3.65E-5	5.0E-6	1.7E-6

The individual source terms and their associated probabilities of occurrence for the above are taken from the "Safety Analysis Report on the Effect of Increased SRB Failure Probability, December 20, 1988, Table 1, items 21 through 88.

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Thus it can be seen that when the SRB failure probability is increased two orders of magnitude, the release expectations for the combined SRB failures increases from 1549 to 7636 Curies or approximately a factor of 5. However, since these type accidents then become dominant in the analysis, the total first stage phase expectation only increases by a factor of 2 from 3,650 to 7729 Curies. For such a high probability of failure for the SRBs relative to the other type accidents, the release expectations for these other potential accidents become almost insignificant in absolute magnitude.

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QUESTION: Describe the methodology of probability risk assessment as applied to these RTGs in laymen's terms so that Committee Members can understand the distinct processes involved in this analysis. In this regard, please describe the failure and abort sequence tree (FAST) as applied to each phase of the mission. How is such a sequence tree used in the safety analysis procedure?

RESPONSE: **GENERAL STRUCTURE AND APPROACH**

The radiological risk assessment performed for the Galileo and Ulysses Missions has several parts, as listed following.

A) Accident Definitions

For each accident, this definition includes the environments (such as explosion overpressure) to which the RTG may be exposed, the probability of the accident occurring and the mission phase in which the accident may occur. The NASA has provided these accident definitions as documented in Reference-1.

B) Accident Model Development and Radiological Releases Calculations

These calculations include prediction of the release in curies of isotope fuel, the location of any calculated release and the physical characteristics of the release (size of particles). This information for a particular case is called a Source Term. The General Electric Company has performed these calculations of source terms for the risk assessment, including development of methodology and analytical models, as documented in References 2 and 3.

C) Radiological Consequence Calculations

These calculations determine the ultimate disposition of the calculated releases in the environment and in biological systems. Part of the results of these calculations include the increased health risk to an individual compared to normal everyday hazards. The NUS Corporation has performed the calculations of radiological consequences and risk for the overall risk assessment, as documented in References 4 and 5.

D) Safety Test Program

The Los Alamos National Laboratory has led an extensive safety test program for the DOE in support of the risk assessment. The general

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purpose of the tests performed is to determine the effects of the various accident environments upon the RTG and to provide data to support accident model development and source term calculation. The test program results as used in the risk assessment are summarized in Reference 2.

PROCESSES INVOLVED IN RADIOLOGICAL RELEASE CALCULATION AND DESCRIPTION OF FAILURE/ABORT SEQUENCE TREES

The Failure/Abort Sequence Trees (FASTs) are logic diagrams which define the sequence of events involving the RTG resulting from each accident defined for the risk assessment, for all mission phases. Each accident has an associated probability of occurrence which is equal to or directly traceable to the NASA-defined values. As a whole, the FAST structure has several levels. The top level is the mission, the second level constitutes the mission phases. Various accidents, which can occur in each phase, represent the third level. Each accident is represented by the FAST as a sequence of events which may lead to fuel release.

Most accidents which may lead to fuel release are explosions of various types, each with characteristics including overpressure, impulse and explosion center, which have been supplied by NASA. A small number of accident cases involve reentry of the RTG from orbit without an explosion. Figure 1 lists the accidents evaluated for each mission phase along with their associated probabilities of occurrence. FASTs for all these cases are presented in Reference 2.

All of the FASTs involving explosions (most of the cases) incorporate the following sequence of events.

A) If the explosion occurs and the overpressure is above 500 psi, the graphite module is stripped from the fueled clads. The fueled clads are undamaged for all overpressures. One branch of the FAST follows the fate of intact (undamaged) modules containing clads. Another branch follows the fate of undamaged clads from which the modules have been stripped.

B) Fueled clads or modules containing fueled clads may be hit by

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projectiles or flyer plates derived from the explosion or not. There are FAST branches again for both bare clads and for modules to represent both possibilities for clads and for modules.

C) Each of the FAST branches subdivide further to trace the ultimate fate of both bare clads and intact modules. Either bare clads or intact modules may strike residual launch vehicle fragments, may strike steel or sand or concrete surfaces around the launch pad, or in later mission phases may impact ocean, ground or rock. All of these possibilities are represented in the FASTs.

Figure 2 is an example FAST for a simple case -- the Centaur CBM explosion in the pre-launch mission phase. The ovals on the diagram represent the events described in paragraphs 1-3 above. Diamonds are shown in the diagram for events for which a fuel release is predicted. Each oval is numbered. The numbers are used to relate tabulated source terms to the corresponding FAST events. Probabilities are associated with each fuel release on the FAST. These are derived from the specified accident probability by analysis. The letters "A", "B" and "C" shown on the example FAST refer to the events discussed previously in this response under paragraphs "A", "B" and "C".

The following discussion follows a particular path through the Figure 2 example FAST to illustrate the logic and approach. This particular FAST represents a Centaur-CBM explosion accident, whose probability of occurrence as provided by NASA is 1.2×10^{-5} (one chance in 83,333), as shown on Figure 1. This information is tabulated on the far left side of Figure 2. The first event represented by the FAST, designated "A", defines whether or not the graphite aeroshell is stripped from the clads; the graphite is lost for explosion overpressures exceeding 500 psi. Following the upper FAST branch, the oval representing no graphite damage is encountered. The lower half of this oval contains the conditional probability of occurrence of this event, which is 0.32. This number is the likelihood, given the original accident has occurred, that the overpressure is below 500 psi and the graphite is not lost. This oval is labeled "GPHS Intact". The conditional probability of 0.32 is obtained directly from the NASA-supplied curve of explosion overpressure

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versus probability, as shown by Figure 3. As can be seen from the dotted line on the figure, the probability of not exceeding 500 psi for the CBM explosion is (1-0.68), or 0.32. The absolute probability of occurrence for the "A" or "GPHS Intact" event is $0.32 \times 1.2 \times 10^{-5}$, or 3.8×10^{-6}. No diamond is shown for this event since no fuel release is predicted.

Continuing to follow the uppermost FAST branch, the next event encountered, designated "B", is labeled "Projectiles Breach FC". This oval represents the case in which intact graphite modules containing fueled clads are struck by projectiles derived from the explosion. Another oval positioned beneath this one represents the alternative of no projectile hits. A diamond follows the uppermost oval, indicating that a fuel release is predicted for the undamaged modules which are struck by projectiles. The probabilities associated with these "B" ovals are the same as reported for the "GPHS Intact" oval, since all of the fuel inventory is divided between the options struck by projectiles or not. This is different than the "A" ovals, which represent the conditional probability of 100% of fuel inventory following one path or the other consistent with the probabilistic explosion data supplied by NASA.

Continuing along the uppermost FAST branch, four event "C" ovals are encountered which document the ultimate fate of the undamaged modules which are struck by projectiles. These ovals represent the modules impacting shuttle fragments (bulkhead), and sand, concrete or steel surfaces around the launch pad. Diamonds indicating fuel release are shown for each of these impacts, since all undamaged modules containing fueled clads damaged by projectiles are predicted to release additional fuel upon surface impact. As can be seen from Figure 2, however, only bulkhead impacts are predicted to result in fuel release for modules not struck by projectiles. The probability of occurrence associated with all of the event "C" impact ovals is the same as that reported for the event "A" GPHS Intact oval, since all of the fuel not released by projectile hits is accounted for among the various impact ovals.

The fuel releases and probabilities calculated for each diamond on the FAST are listed in the source term tables presented in References 2 and 3.

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Further information concerning the mathematical models employed to calculate the fuel releases is presented in the response to the next question. Full descriptions of these models, including sample calculations and assumptions, are provided in Reference 2.

In summary, the overall risk assessment is comprised of three parts. including accident definition, accident modeling/source term calculation and radiological consequence calculations. The FAST's are used in calculation of the source terms to completely define the various possible fates of the RTG for each of the accidents specified.

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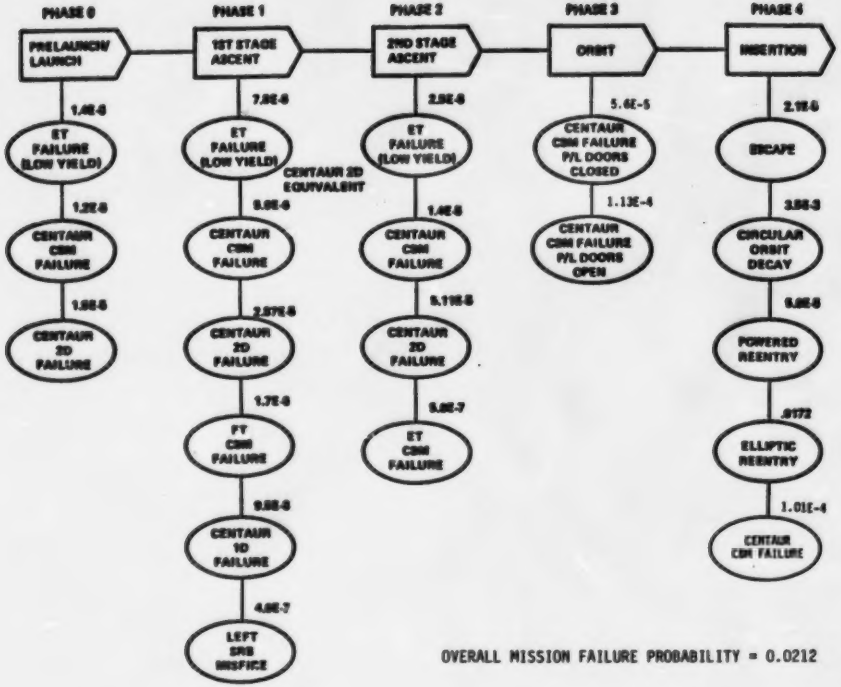

FIGURE 1. MISSION ACCIDENT PROBABILITIES

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FIGURE 2. TYPICAL FAILURE/ABORT SEQUENCE TREE (FAST)

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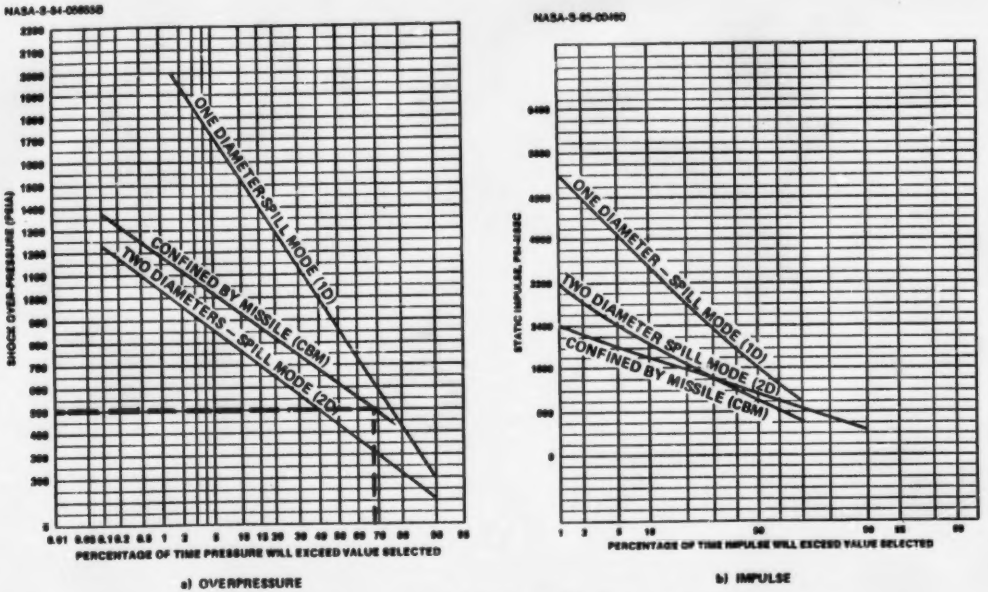
NASA-S-64-00859
SHOCK OVER-PRESSURE (PSIA)
ONE DIAMETER SPILL MODE (1D)
CONFINED BY MISSILE (CBM)
TWO DIAMETERS – SPILL MODE (2D)
PERCENTAGE OF TIME PRESSURE WILL EXCEED VALUE SELECTED
a) OVERPRESSURE
NASA-S-65-00460
STATIC IMPULSE, PSI-MSEC
ONE DIAMETER – SPILL MODE (1D)
TWO DIAMETER SPILL MODE (2D)
CONFINED BY MISSILE (CBM)
PERCENTAGE OF TIME IMPULSE WILL EXCEED VALUE SELECTED
b) IMPULSE

Figure 3. Empirical Shock Over-Pressure and Impulse Models for Centaur Explosions

QUESTION: Please explain the failure and abort sequence tree methodology for characterizing failure modes for each phase of the shuttle launch. As these sequence trees are used to establish three levels of radiological release, could you explain for the members the physical significance of most probable release, expected release, and maximum release numbers?

RESPONSE: The Question asks for explanation of "expected release", "most probable release" and "maximum release" numbers. The FSAR terminology does not include the nomenclature "expected release". Two categories of release numbers are reported for each FAST release event, as defined following:

1) Predicted Release, and
2) Maximum Release.

In addition, three categories of release numbers have been reported for each mission phase, derived from the predicted and maximum release numbers for each FAST event, as defined following:

4) Release Expectation Case,
5) Most Probable Case, and
6) Maximum Case.

The Radiological Risk Analysis presented in Volume III of the FSAR (References 4 and 5) is based upon the mission phase release numbers (items 4, 5 and 6). It is assumed, therefore, that the Question refers to items 4, 5 and 6. The following explanation, however, deals with all five categories of release.

The philosophy and structure of the Failure/Abort Sequence Tree (FAST) methodology, as it relates to source term calculation, is included in the response to the previous question. The analysis methods used to predict the magnitudes of fuel release consistent with the FASTs are described in this response, as necessary to explain the significance of the various categories of release.

As described in the response to the previous Question, the FASTs incorporate explosion damage events, events involving damage by projectiles and events involving impact of fueled clads or of modules on various surfaces.

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The analysis to define the probability of losing module graphite is directly calculated using the NASA-specified relation of explosion overpresure versus probability (for each accident) along with safety test program data showing the modules are undamaged below 500 psi overpressure. No fuel releases are predicted due to explosion overpressure alone for the full range of overpressures specified. In addition to overpressure effects, no fuel releases are predicted due to fireball effects either, also based upon extensive safety test program experiments.

The analysis to evaluate projectile impacts upon bare fueled clads and/or intact modules is much more complex. For each accident, the location of the center of explosion is required to calculate the trajectories of the fragments specified by NASA and, thereby, to determine whether or not any fragment will strike the RTG. The variation in the centers of explosions are specified as volumes and/or regions rather than single points. Furthermore, a particular explosion can have a range of overpressures as a function of probability. The analysis approach employed in the FSAR deals with this complexity by calculation of a very large number of cases, using random selection of explosion location and overpressure consistent with the NASA-specified information. For cases where the RTG is predicted to be hit, additional calculations are performed to determine whether the particular fragment will penetrate the fuel cladding and release fuel. These latter calculations are supported by safety test program experiments involving impact of fuel assemblies by various projectiles.

The analysis methods employed to determine the fate of damaged and undamaged bare fueled clads and intact modules are also complex. Center of explosion locations and explosion overpressure are also needed for this calculation to define the trajectories and velocities of fueled clads and modules (damaged and undamaged) which are ejected by the explosion. This situation is evaluated by calculation of a very large number of cases to determine the fraction of ejected clads and modules which impact on the various surfaces (sand, steel, vehicle fragments, ocean, rock or soil). Using the distribution of impacts and impact velocities derived from the trajectory analysis, data and data correlations

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obtained from the safety test program are employed to predict the quantity of fuel release, if any.

The predicted release values tabulated in the safety reports for each FAST event are the averages of the many randomly-selected cases calculated as described above. The predicted release values for the Figure 2 example FAST are listed on page 3-72 of Reference 2, Volume II and on page K-1 of Reference 3. These values are believed to be the most significant and useful results. They represent the best estimate of what will occur on the average, if a particular accident happens. These values can be added over the several FASTs (several accidents) in a mission phase by probability weighting to provide predictions of the average release for the entire phase if an accident should occur. This probability weighted average release for each phase is the release expectation case. An average release or expectation for the entire mission (should an accident occur) can also be calculated. These are the values, called expectations, which are tabulated in the FSAR (References 2 and 3) and which form the principal basis for the risk assessment. Table 3.4-5, pg. 3-227 of Reference 2, Vol. II, Book 2 and Tables 2-1 through 2-4 of Reference 3, pgs. 2.5 to 2.8, present these phase expectations.

The maximum release values listed in the safety report FAST source term tables were selected as the largest releases obtained from the many randomly-selected cases calculated for each FAST event. These maximum release values for the Figure 2 example FAST are listed on pg. 3-72 of Reference 2, Volume II and on pg. K-1 Reference 3. The probability of the maximum release is less than the probability of the expected release. The maximum release values provide an indication of very low probability upper limit occurrence. They are not, however, an absolute upper limit, only the largest value calculated for a very large number (1000's) of randomly-selected trials. For some FAST events, probabilistic calculations did not provide the data for definition of a maximum. For these events, the maximum release is taken equal to the predicted value.

The most probable release case, presented at the phase level and used

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in the risk analysis, is selected based upon the phase FAST sub-branch with a predicted fuel release for an event having the highest probability, independent of release magnitude. This case includes any associated or sequentially related source terms in the FAST branch. The most probable release case is the sequence of events and releases which are most likely to occur, given that an accident happens in a particular mission phase. The most probable release cases for each mission phase are listed in Table 3.5-1 and 3.5-3 (pgs. 3-230 and 3-232) of Reference 2.

The maximum case, presented at the phase level and used in the risk analysis, is selected based upon the phase FAST sub-branch having the highest maximum release for an event. This case includes any associated or sequentially related source terms in the FAST branch selected to maximize the risk. This maximum case for each mission phase is the sequence of events, independent of probability, which yields the largest releases and/or is anticipated to yield the highest risk. It is believed to approximate a low probability upper limit scenario. The maximum cases for each mission phase are listed in Tables 3.5-2 and 3.5-4 (pgs. 3-231 and 2-233) of Reference 2.

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QUESTION: Returning to the adequacy of the data base utilized to caluclate nuclear risk associated with RTG flights on board the Shuttle Spacecraft, are there any additional testing activities that should be undertaken during the hiatus we apparently will have before an actual Galileo flight can be launched. Such tests would significantly expand our knowledge about potential accidents and thereby improve our statistical calculations as they relate to the risk associated with flying these RTG systems?

RESPONSE: The highest predicted release expectations during the prelaunch and ascent phases of the mission are associated with the collision of the isotope heat source with orbiter components at high velocity as a result of an explosion of the Centaur. In the FSAR analysis, it was assumed that these collisions would be equivalent to impacts on concrete because a data base for impact on aluminum was not available. The assumption used is very conservative. Therefore, it is important to obtain collision or impact data for the heat source on Shuttle materials such as aluminum with configurations and thicknesses representative of those on the Shuttle. This would be the most important area where additional testing would improve our statistical calculations as they relate to the risk associated with flying RTGs.

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REFERENCES

1. JSC-08116, "Space Shuttle Data for Planetary Mission Radioisotope Thermoelectric Generator (RTG) Safety Analysis", NASA Johnson Space Center, April 15, 1985.

2. GESP-7200, "Final Safety Analysis Report for the Galileo Mission and the Ulysses Mission", October 8, 1985, Volume I and Volume II, Books 1 and 2.

3. GESP-7200, "Final Safety Analysis Report for the Galileo Mission and the Ulysses Mission", December 17, 1985, Supplement to Volume II (Book 1) Accident Model Document.

4. GESP-7201, "Final Safety Analysis Report for the Galileo Mission and the Ulysses Mission", October 23, 1985, Volume III, Books 1 and 2.

5. GESP-7201, "Final Safety Analysis Report for the Galileo Mission and the Ulysses Mission", December 17, 1985, Supplement to Volume III, Book 1, Nuclear Risk Assessment Document.

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PETER J. VOGELBERGER, JR. President

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28 March 1986

Refer to: TES-PJV-194

APR 03 1986

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The Honorable Marilyn Lloyd
Chairman
Subcommittee on Energy Research and Production
Committee on Science and Technology
U. S. House of Representatives
Rayburn House Office Building, Suite 2321
Washington, DC 20515

Dear Congresswoman Lloyd:

I appreciated the opportunity to testify at your hearings on the use of RTG's in space.

Enclosed herewith is our answer to the additional question forwarded in your letter of 19 March.

We are attempting to find an interested sponsor to support all or part of this probabilistic risk assessment work and the necessary background data which we have recommended.

Please feel free to have your staff contact me if there are any questions or if we can be of further service.

Sincerely,

Peter J. Vogelberger, Jr.

nmm

enclosure (1)

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March 26, 1986

Response to Chairman Lloyd's Question:

QUESTION FOR TELEDYNE

As a result of your studies, do you believe that additional work would be beneficial in this area in order to provide a more meaningful statistical calculation of failure probabilities? What additional work would be recommended, if any, that could further improve our estimation of the probabilities assigned to the failure modes?

ANSWER Yes, we feel that additional work would be beneficial.

Information related to accident probabiiities has been placed in two categories in the prior reviews by SERA and Sandia: SRB failure probability and failure rates for other vehicle modes. Additional work would be beneficial in each area.

1. SRB Failure Probability

It has been shown that generic historical data imply a failure probability greater than 0.01 for case or nozzle burn-through modes. There is some evidence that ignition failure may have a similar probability based on the same generic data sources. In our opinion, the solid motors should have a total failure probability which doesn't exceed 0.001, considering the total number of flights planned and the risk potential for those missions which include nuclear power sources. To measure the SRB system against this 0.999 reliability objective, we suggest the following work.

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a. Review existing failure modes and effects analyses (FMEA) which have been done at some level by NASA and its contractors. Objective of the review is to ensure that all critical modes have been identified.

b. Examine test and experimental data pertinent to mechanisms which cause the identified failures. In this case objectives are to make sure there are data pertinent to each mechanism and that the data show a margin of safety - i.e. excess "strength" relative to uncertainty in environmental "loads" - consistent with the reliability goal.

c. Perform additional tests where available data are insufficient.

If the data do not show achievement of the reliability standard, hardware changes in the SRB system or procedural improvements in its use should be incorporated.

2. Failure Rates for other Vehicle Modes

As indicated in our review of the SERA and Sandia studies, there is evidence that component failure rates used by Wiggins are more uncertain than assumed in its study. If this is the case, probabilities for the significant accident scenarios may exceed the reasonable standard suggested above. The following additional work should be accomplished:

a. Review thoroughly failure rates used in Wiggins' study. Uncertainties for each component or failure mode should be evaluated individually. Other data sources should be elicited where possible.

b. Perform qualitative fault tree analyses where the top events are the significant accident scenarios, thus eliminating the intermediate Vehicle Response Modes.

c. Assemble failure rates using the Monte Carlo approach with the improvements recommended by SERA and Sandia. The assembly should be oriented toward the complete set of accident scenarios derived as part of (2.b).

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In categories 1 and 2, the omissions pointed out by SERA:

- common cause failures
- maintenance errors and failures
- personnel errors, and
- preexisting failures

should be taken into account. Performance of the above tasks would be useful in measuring vehicle reliability for critical failures. Should the resulting probabilities be unsatisfactory it would be apparent where design improvements or administrative controls would be effective.

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Representative Marilyn Lloyd, Chairman
Subcommittee on Energy Research and Production
U. S. House of Representatives
Committee on Science and Technology
Suite 2321 Rayburn House Office Building
Washington, DC 20515

Dear Representative Lloyd:

As requested, this letter summarizes the results of the safety tests that the Los Alamos National Laboratory conducted on the General-Purpose Heat Source (GPHS). The tests were carried out in support of the Galileo and Ulysses missions. We believe that the testing has established a self-consistent data base that allows the response of the GPHS to the various accident environments to be predicted with a degree of conservatism. We have issued formal testing reports covering some of these tests and we are preparing reports on the heat source's response to the other tests. Throughout this program, all of the technical information was presented as briefing packages at many formal and informal meetings.

I. Explosion

The original test plan called for the determination of the fuel-containment capability of the GPHS module in an explosion environment, starting at 200 psi and progressing to 2000 psi. We exposed bare modules to increasingly severe overpressures in a Sandia National Laboratory high-explosive-driven shock tube. The tests demonstrated that 200 psi did not damage the module, whereas 735 psi cracked the outer graphite, but released neither the fueled clads nor the impact assemblies. The pressure of 1070 psi, however, removed all of the graphite components from the fueled clads, but did not breach them. A soft-recovery catch tube was used, so the recovered objects showed the effects of only the explosion.

This test series was suspended after the 1070-psi test until the results of the DIRECT COURSE test were known. DIRECT COURSE proved to be of no value in elucidating the response of the heat source to explosions, but during the study that followed, it became clear that the converter assembly might not provide added protection, but might actually increase the severity of the explosion environment.

Accordingly, when the shock-tube tests were resumed, sections of the converter housing, the insulation and the thermoelectrics were placed between the heat source and the explosion. These components are always present when the heat source is on the launch

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vehicle and, therefore, they represent a constant source of close-in fragments in any explosion large enough to disrupt the converter.

Nine such tests were run in the pressure range of 429 to 2212 psi. The results verified that the presence of the converter assembly intensified the environment. At 429 psi, the reentry shell was cracked, but not removed (this occurred at 735 psi without the converter). At 736 psi, all of the graphite components were removed (this occurred in the 1070-psi test of the bare module). Not all of the tests were completed successfully and not all of the fueled clads were recovered after the successful tests, but the available evidence indicates that even the highest pressure (2212 ±220 psi) was not sufficient, by itself, to cause a fuel release. It is evident, however, that the fueled clads are propelled through the air and are subject to subsequent impact damage if they collide with a hard surface. They are also subject to being struck by an explosively-driven fragment, which might cause added damage. The fueled clad's response to those environments is considered below.

Although the explosion alone does not break the clads and release the fuel, it does not leave them unaffected. The explosion overpressure squeezes the clad onto the fuel and reduces or eliminates the gap between them. This effect becomes more pronounced as the pressure increases.

The other RTG components were destroyed in all of the tests. The thermoelectric elements and the insulation were fragmented into pieces smaller than 12 mm. The aluminum-alloy housing fragmented into pieces whose sizes were inversely proportional to the pressure (33.1 g at 429 psi and 0.7 g at 2212 psi).

II. Fragment Impact

The fragments that would be formed by the explosion of a launch vehicle could represent an added mechanical insult to the heat source. Fragment size, shape, velocity and material are all functions of the particular vehicle and accident. The range of combinations is too large to be covered completely, so the fragment impact tests were limited to specific compact and extended fragments of materials found in the Shuttle.

Twenty fragment impact tests were conducted using three types of fragment. The compact fragments were represented by a blunt-nosed, 18-g aluminum alloy bullet (50 cal.) made from the same alloy as the Shuttle external tank and a blunt-nosed 3.3-g titanium alloy bullet (30 cal.), which closely matched titanium fasteners on the spacecraft. The extended fragments were aluminum-alloy plates of 3.2, 3.5 and 38 mm thick. The targets consisted of GPHS module graphite, GPHS modules, GPHS clads containing UO_2 and a copper simulant of a fueled clad. The bullet tests were conducted at the Los Alamos firing range and the sheet-fragment tests were conducted at the Sandia National Laboratory test range.

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The aluminum bullet was propelled through layers of nodule graphite to determine how much that material would degrade the velocity and shape of the fragment before it encountered the fueled clad. The kinetic energy decrement was found to be inversely proportional to the velocity, falling from 47% at the lowest velocity (357 m/s) to only 18% at the highest velocity (950 m/s). The bullet deformation was found to be directly proportional to the velocity, ranging from 2% at the lowest velocity to 36% at the highest. Thus, compact fragments that impact nodules would be slowed and deformed before they hit the clads, both effects would reduce their capacity to breach the clad and release the fuel.

Five aluminum-bullet tests were conducted against preheated (1090°C) GPHS modules at velocities ranging from 319 to 555 m/s. The latter velocity is that at which the clad was breached by the kinetic energy of the fragment. In some of the lower-velocity tests, the bullet lodged in the graphite adjacent to the clad, melted and reacted with the clad. The degree of reaction was controlled by the time the aluminum remained in contact with the iridium clad, which depended on the orientation of the module during the cool-down period after the test. The reaction did not cause a release of UO_2.

Three titanium-bullet test were conducted against preheated (1090°C) UO_2 clads at velocities of 423, 446, and 684 m/s. The lowest velocity just initiated a breach of the clad, while the highest velocity, corresponding to about 2.6 times the energy, breached the clad and released 13.5% of the UO_2. The test conditions imposed a step change in fragment momentum per unit area and were based on possible bolt fragments originating between the explosion center and the RTG's within the Shuttle bay.

The extended fragment tests on the GPHS consisted of four explosively driven aluminum-alloy flyer plate tests and two rocket-propelled tests. In addition, a rocket test was run with a copper clad simulant to provide data for a proposed computational fragment impact model being developed by others.

Three of the flyer plates, 3.5 mm thick, were propelled against preheated (1090°C) UO_2 clads at velocities of 349, 624, and 1173 m/s. At all velocities tested, the clad were breached by small transverse cracks on the impact face, but in no case was more that 0.05 g of UO_2 released. The flyer plates were destroyed in the tests. A clad-sized hole was punched out of the center of each plate and the remainder was fragmented. The plate's fragment size decreased as the test velocity increased.

A single 38-mm thick aluminum plate was propelled against a preheated clad at 271 m/s. The clad was breached and the entire UO_2 content was released. The test thickness was supposed to represent an aggregate thickness of several aluminum-alloy sections on the Shuttle; no single section is actually that thick.

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A 3.2-mm thick aluminum-alloy plate was driven by the Sandia rocket sled at 915 m/s edge-on into the side of a full GPHS module. The test conditions were in response to a Launch Abort Subpanel test recommendation of a credible accident fragment and module interaction. The plate sheared through all four clads and released their entire UO_2 contents. The plate, too, was sheared into several pieces. Several engineering tests were required before Sandia developed a way to hold the plate in the required edge-on orientation, because the aerodynamic forces at that velocity impart a plate spin after just a few centimeters of free flight.

Two tests were run in support of fragment modeling work of others. In the first such test a 3.2-mm-thick aluminum alloy plate was propelled edge-on into a copper fueled-clad simulant at 148 m/s. The plate penetrated 61% of the copper sample's diameter. A 3.5-mm-thick aluminum-alloy plate was then propelled edge-on into a preheated (1090°C) bare UO_2 clad at 142 m/s. The plate penetrated 7% of the fueled clad's diameter and breached the clad; 24.6% of the UO_2 was released.

III. Bare-Clad Impact

Because larger explosions would propel free fueled clads through the air, we conducted tests in which bare fueled clads were impacted against steel, concrete or sand. Six $^{238}PuO_2$-loaded clads and nine UO_2-loaded clads were used in the tests.

The PuO_2 fueled clads were conditioned at 1287°C for 200 h and impacted at 1091°C, the temperature of the heat source in the launch configuration. Four were impacted against concrete that had been cored from a launch pad at the Kennedy Space Center and two were impacted against hardened steel targets.

The clad impacted at 53 m/s on concrete did not breach. There were two small cracks on the impact face of a 65 m/s sample (total crack area: 1 mm^2). A 76-m/s sample breached on the front, back and weld (288 mm^2 area) and a 90-m/s sample failed on the front and back (67 mm^2 area). The former clad was contaminated by the holding fixture while it was being heated prior to the impact. The large breach is, therefore, not typical of the bare-clad impact performance.

Two of the PuO_2 clads were impacted against hardened steel at 53 m/s; both breached. The crack size in one was 0.33 mm^2 and in the other the crack area was 4.4 mm^2. Thus, it seems reasonable to say that the failure threshold for a bare PuO_2 clad impacting perpendicularly on a concrete target is just below 65 m/s and that for a similar impact on hardened steel the failure threshold is close to 53 m/s.

Four of the UO_2 clads were impacted in the as-fabricated condition, in which case they were closely similar to the PuO_2 clads, and five of the UO_2 clads were impacted after recovery from explosion tests, in which case they had some of the characteristics

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that real fueled clads would have in a launch vehicle explosion that stripped away the converter and the graphite.

Four of the as-fabricated UO_2 clads were impacted on steel at 54 m/s. The results closely paralleled the PuO_2 test results. Two of the samples did not breach and two of them did breach. The crack sizes in the failed samples were 0.6 and 1.1 mm^2. Thus, the UO_2 appears to have been a good simulant for the PuO_2 in the impact tests.

One as-fabricated UO_2 clad was impacted at 160 m/s against a concrete target made at Los Alamos. The weld failed completely and all of the fuel was released. One clad cup was recovered in a single piece and the other was recovered in three pieces. Because of the massive weld failure, we learned nothing from this test and consider it invalid. However, the FSAR projected full clad release level of 148 m/s is consistent with this test result. We believe that the full release projection to be conservative based upon results of the other concrete target tests in the bare clad impact series.

One UO_2 clad that had been recovered from a 1750-psi explosion test was impacted against hardened steel at 54 m/s. It failed on the front and on the end (42-mm^2 area).

One UO_2 clad that had been recovered from a 500-psi explosion test was impacted against Los Alamos concrete at 117 m/s. The impact caused a small crack (0.6 mm^2).

Two recovered UO_2 clads were impacted against sand; neither failed. One was impacted at 206 m/s after exposure to an unknown pressure in an aborted explosion test and the other was impacted at 250 m/s after an exposure to 1070-psi. Slight clad surface abrasion was noted in both tests. Also, these sequentially tested fueled clads did not exhibit added deformation from the sand impact. On the basis of the observations, fuel containment margin existed at the 250 m/s impact velocity. The cited results were not available at the FSAR issue date but it is clear that the assumed 200 m/s clad breach threshold for sand impact was markedly conservative.

The as-fabricated UO_2 samples appear to be good simulants. We do not know if the UO_2 samples that were exposed to explosions before impact behaved the same as PuO_2 samples would have, because safety constraints make it impossible to expose PuO_2 samples to explosions. We believe that the UO_2 impacts against sand can be taken as indicative of the PuO_2 response. Modest clad abrasion was noted and the lack of deceleration clad deformation indicated that fuel containment margin existed at the highest sand impact velocity.

IV. Fires

In an accident, the GPHS could be exposed to fires from the liquid propellants or the solid propellants. The latter is the more severe, so the GPHS tests were run with it. A GPHS impact assembly

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and a UO_2 bare clad were preheated to 1100°C and exposed to a 10.5-minute single proximity solid propellant fire. We did not have the actual propellant used in the solid rocket motors on the Space Shuttle. Instead, we used the closely similar UTP-3001 propellant that fuels the solid rocket motors used with the Titan vehicle.

The clads inside the graphite impact shell were tarnished, but otherwise undamaged. The corner of the bare clad that had faced the burning face of the propellant reacted with the test environment. The reaction reduced the clad thickness only 15% and none of the UO_2 was released.

V. Module Impact

The GPHS module is the characteristic unit of the heat source that will reenter the atmosphere and impact the Earth's surface in the event of an exoatmospheric accident. In the GPHS safety test program we simulated both prompt (minimum-gamma) reentry and orbital-decay reentry accidents. The two sets of conditions that we used for the tests were provided to us by General Electric Company. We aged the impact assemblies, subjected them to the heat they would be exposed to in reentry, reassembled the module with reentry shells machined to simulate the graphite ablation that would occur during a reentry and impacted them at 54-55 m/s (one was tested at 73 m/s).

Thirteen modules were tested. The test variables included the type of accident, prompt or orbital decay reentry, the orientation of the module, and the target material. Each module contained four PuO_2 fueled clads. Two were prime, flight quality and two were nonflight quality. Two modules were tested in the prompt (minimum-gamma) reentry mode. They were aged at 1287°C for 200 hours and impacted against hardened steel at 919°C. In both cases, one of the large faces was parallel to the target (0°). In the first test both nonflight clads breached (25-mm2 total area). In the second test one nonflight clad failed (8-mm2 area). None of the prime clads breached. In the orientation cited, all the clads in each test receive the same impact load. Clad breaches in the two tests cannot be ascribed to closure weld characteristics; the basis for discrimination between flight and nonflight quality clads. Results are valid for the tests and the fuel releases should be indicative of those possible for the test conditions imposed by this reentry mode.

The remaining eleven modules were tested in the orbital-decay mode (90 day at 1287°C followed by a 975°C impact). Eight were impacted against steel targets, two against concrete and one against granite.

Two steel-target modules were impacted in each of four different orientations, flat-on (0°), and tilted 15°, 30°, or 90° to the target with the axes of the impact assemblies parallel to the target.

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In the 0° impacts, one of the nonflight clads breached (0.4 mm^2) in the first test and one of the prime clads failed (1.8 mm^2) in the second test.

In one of the 15° tests one prime clad and both nonflight clads breached (53 mm^2 total area) and in the other the prime clads were intact, but both nonflight clads breached (54 mm^2 total area).

In the 30° tests none of the clads breached.

In the first 90° test none of the clads breached, but in the second 90° test one of the prime clads breached (24 mm^2).

The clads were designated as prime or nonflight on the basis of an ultrasonic inspection of their welds by the manufacturer, Savannah River Plant. There was no significant difference between their impact performances except in one of the 15° samples in which the weld failed at a low strain. We believe that the two types of clad can be considered as part of the same population. Thus against steel at th 54 m/s level, the failure rates were 7/16 at 0°, 5/8 at 15°, 0/8 at 30°, and 2/8 at 90°.

A single orbit-decay test was run at 0° against a granite target at 54 m/s. One prime clad failed (8 mm^2). The single test is not sufficient to draw a firm conclusion, but the granite appears to have approximately the same effect as the steel target.

Two orbit-decay tests were performed at 0° with a concrete target. None of the clads failed at 54 m/s, but one prime and one nonflight clad failed at 75 m/s (17 mm^2 total area). These results indicate that concrete is a more forgiving target than either steel or granite. An analysis for the FSAR, based on the results of bare clad deformations in impacts against steel and concrete, ascribes a 1.4 multiple to the degree of test target severity. No such multiple should be applied to module impacts, but the order of target character was correctly predicted in the FSAR analysis.

V. Impact Fuel Releases

We determined the amounts of fuel released from the clads in the module impact tests and the amounts of fuel or uranium oxide released from the failed clads in the bare-clad impacts.

In the 54-m/s steel-target module impacts, a total of 0.3037 g of fuel was released from the seven modules in which clads were breached, an average of 0.0723 g per module. Smaller amounts were released in the granite impact, 0.0149 g, and the 75-m/s concrete impact, 0.0290 g. An average of 0.0024 g of fuel was found in the graphite of the four impacted modules that had no clad breaches.

This presumably came from the fuel remaining on the iridium after the manufacturing process and the fuel that effused through the the vents during the 90-day aging treatment. We believe that much of the released fuel was mechanically adhered to the graphite.

The bare-clad impacts were run with the intent of determining both impact capability and fuel releases. The former are discussed above. The releases determined in the valid tests ranged from zero near the failure thresholds to 14 g in the 76-m/s PuO_2 impact on concrete.

VI. Particle Sizing

Throughout the testing of the GPHS, we have maintained a strong emphasis on determining the particle sizes of the fuel and the fuel simulant in both breached and unbreached clads. We determined the size distributions of the fuel or simulant in unbreached clads and the size distributions of the fuel or simulant released by a test that led to a clad breach.

One example will illustrate the scope of the particle size measurement effort. The individual plutonium releases in the 13 flight module impacts ranged from 0.0020 grams to 0.2227 grams. For all impacted modules (6,865 grams of plutonium tested), a total of 0.5593 grams was released through clad cracks. The clad crack width restricts the particulate sizes which can be released. Consequently, the 10 um plutonium particles released were, conservatively, 0.3768 grams total. Consideration of the 4 um particles as potentially respirable material, further centers interest on a total of 0.1115 grams of plutonium.

Each particle size analysis typically extended to 22 size fractions, which provided measurements for compilations and analyses much more detailed than the simple illustration indicated.

These results and two dozen others have been reported in formal and informal reports, in letters and in handouts at meetings. They are too voluminous to summarize in this short letter, but the reporting of them in formal reports will be completed shortly.

In summary, a tremendous amount of effort went into providing data for the safety analyses of the GPHS for the Galileo and Ulysses missions. The formal testing of the production heat source followed protracted programs of safety-related testing during both the

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prototype design phase and the flight design phase. The GPHS has been subjected to the most exhaustive test program of any radioisotope heat source. It has proven to be highly resistant to accident environments.

If you have any additional questions about the safety testing of the General Purpose Heat Source, please contact me.

Yours truly,

R. W. Zocher
Physical Metallurgy Group

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Sandia National Laboratories
Albuquerque, New Mexico 87185

April 4, 1986

The Honorable Marilyn Lloyd, Chairman
Subcommittee on Energy Research and
Production
U.S. House of Representatives
Rayburn House Office Building
Suite 2321
Washington, DC 20515

Dear Chairman Lloyd:

I appreciate the opportunity to supplement my March 4, 1986, testimony by responding to your letter of March 19, containing further questions from the Subcommittee. My response contains two parts. First is a point-by-point response to your questions. Ron Iman, statistician, has supplemented this with additional technical details.

Should you desire further information, please call me at (505) 296-1370.

Sincerely,

David D. Carlson

David D. Carlson, Supervisor
Light Water Reactor Safety
Technology Division 6417

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Responses to Questions from the Subcommittee on Energy Research and Production

- **Could you please explain for the Committee the significance of the 60 percent confidence limit as opposed to the 90 percent confidence limit for calculating probabilities as discussed in the two reports?**

The confidence limit reflects the amount of uncertainty in an estimate of a failure rate. A statement of 60 percent confidence means that there is a 60 percent chance that the failure rate falls within the given range of estimates; similarly, a 90 percent confidence limit means that there is a 90 percent chance that the failure rate falls within the given range.

The Wiggins' and SERA's reports disagreed on the interpretation of confidence limits to be applied to component failure rate data. Both used the data base compiled for the Reactor Safety Study. Wiggins assumed that the given bounds represented 90 percent confidence limits (consistent with historical interpretations); SERA argued that the given bounds for some of the data should be interpreted as 60 percent confidence limits due to greater uncertainty for the shuttle analysis.

This assumption can have a dramatic effect on the estimated failure rate. In the example we examined, the estimate of the mean failure rate increased by a factor of 500 when assuming 60 percent rather than 90 percent confidence limits. The overall effect on shuttle failure rate estimates depends on the number and types of components and the associated data base. Nevertheless, of all the issues that we examined for failure modes other than solid rocket booster failure, this had the potential for the greatest effect on the failure rate estimates.

SERA supports their claim with two arguments:

1) "the overwhelming evidence from research is that people's probability distributions tend to be too tight...and prone to bias;" and

2) More recent risk assessments for nuclear power stations have concluded that the Reactor Safety Study distributions should be broadened to reflect greater uncertainty.

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We found neither argument persuasive. The first statement is true and is often cited in estimates derived from soliciting informed opinion. However, the Reactor Safety Study failure rate values were based upon a number of compilations of historical data, not based upon subjective estimates from informed opinion. Thus, the first argument does not apply.

Our review of the Indian point Probabilistic Safety Study, cited by SERA as a precedent for their second argument, found that the authors were not consistent in their usage of 60 percent rather than 90 percent confidence limits. In particular, for many of the types of components that prevail in Wiggins' analysis for the shuttle--pressure vessels, pipe ruptures, certain valves--the Indian Point Probabilistic Safety Study authors assumed 90 percent intervals. Furthermore, the applicability of precedent from a nuclear power plant risk assessment was not well supported.

Therefore, it is our opinion that the SERA report does not provide sufficient arguments to warrant changing the uncertainty intervals used by Wiggins.

This subject is discussed in more detail on pages 30-34 of the Sandia report and in the supplement to this response.

- Dr. Carlson, as you know, the SERA study calculated a value for SRB failure probability that was at least two orders of magnitude larger than the numbers utilized in the NASA shuttle data book. The Sandia analysis indicated that this calculation could not be analytically supported. Could you describe for us, hopefully in laymen's terms, exactly how you came to this conclusion?

Both Wiggins' and SERA's estimates utilized experience with earlier solid rocket boosters to develop an estimate of the solid rocket booster failure rate for the shuttle. Their estimates differed by more than a factor of ten. This difference arose primarily from Wiggins' assertion that the failure rate has decreased over time as experience has been obtained with various types of solid rocket boosters and improvements have been made. SERA's approach did not consider improvements over time.

While the technology may have improved over time and hence Wiggins statements may have some validity, their report provided no analytical justification for their estimates. (We did not conclude that the statements could not be supported.) Wiggins provides a summary of historic data

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that, on face value, suggests a failure rate of between .017 and .029 per SRB firing (i.e., between 1 in 59 and 1 in 34 chance of failure per firing). The Wiggins' report provides the following justification for their estimates of .001 and .0001 (one chance in a thousand and one chance in ten thousand):

> "The adjustment of the historical solid rocket motor failure probability for application to the Space Shuttle SRBs was an engineering judgment involving the Space Shuttle Range Safety Ad Hoc Committee [7]. It was realized that the 'learning curve' for solid rocket motor technology has resulted in more reliable motors. Since the historical data includes motors developed 10 to 20 years ago, it was decided that a reduction in the failure probability estimate was warranted for the Space Shuttle SRBs. Based primarily on this, it was decided to assume a failure probability of 1×10^{-3} for each SRB. (Note that this is the total probability of a failure during the operating time of the SRB, about 120 seconds.) Due to the dominance of the solid rocket motor case/nozzle failure probability relative to the probability of failure due to other types of failures, and due to the high degree of uncertainty in the failure probability estimate, it was decided by the Ad-Hoc Committee that a second probability should be considered in the hazards analysis which is one order of magnitude less. Thus, a value of 1×10^{-4} per SRB is also considered. It was argued by some that the lower SRB failure rate is justified due to unique improvements made in the design and manufacturing process used for these motors to achieve man rating."

Not being a party to these discussions, we could not evaluate the validity of these judgments. No analysis was provided to support these judgments, although statistical techniques exist for incorporating learning into such estimates. Furthermore, the weakest of the set of estimates--the one in ten thousand estimate--appears to have been the one carried through the remainder of the safety analysis.

SEHA's approach precludes incorporation of "learning" into their estimate. Thus, if technology has improved over time, their approach would overestimate the failure rate. There were some additional concerns over their approach. These are discussed in the attached supplement.

The subject of the estimate of solid rocket booster failure rates is discussed in greater detail on pages 36-46 of our report and in the supplement.

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- NASA has indicated that application of statistical analyses to shuttle failure modes would significantly overestimate the failure probabilities and, therefore, do not provide a realistic method for assigning probability values to various accident scenarios. They prefer to use engineering judgment. Do you believe that an adequate data base could be established or does an adequate data base exist, which would permit a meaningful statistical analysis of shuttle failure rates and accident scenarios?

Another related question:

- It is our understanding that NASA's normal procedures do not involve assigning probabilities to various failure modes associated with a potential shuttle accident. Rather, they use engineering judgment to estimate whether a particular component or element of the shuttle spacecraft will fail under various environments and operating conditions. Is there sufficient information in the data base to make a meaningful probability assessment?

There are several elements that must be considered to assess the probability of various accident scenarios. First of all, one must define the scenarios of concern. Then one must ascertain the ways in which such scenarios can occur, e.g., what combination of equipment failure can lead to this scenario. Finally, one must collect data to estimate the probabilities of the individual faults and, ultimately, to calculate the scenario probabilities. Throughout this process there are many unknowns and uncertainties. These arise, for example, from the analyst's ability to define the scenarios, the completeness of the investigation of failure modes, and the adequacy of the data base. The true value of the assessment lies in the systematic review of the design and the insights into weaknesses of the design that such a process surfaces. Prudent improvements can then be made.

With regard to the adequacy of the data, ideally one would like to have a substantial data base for components in applications similar to those for which they are going to be used. That is, one would like to have data on structural, electrical, and mechanical components under the same stresses and environments that they would see in the shuttle. The specific nature of such a data base limits the amount of data available.

In the absence of the ideal, the analyst can use data on similar components used in other applications. This is what both SERA and Wiggins did with their use of Reactor Safety

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Study data. (By the way, this was the most comprehensive data available at the time of the Reactor Safety Study and included data from military and aerospace applications.) SEHA suggested modifying the failure estimates by applying multipliers to account for more stressful operating conditions. For many components used in the shuttle, such a data base exists. Applying multipliers and the choice of appropriate multipliers is a matter of judgment.

In the absence of data, analysts rely upon "engineering judgment" for failure rate estimates. This is based upon the analyst's experience with similar components or with other applications and is inherently subjective. The quality of the estimates is only as good as the judgment of the engineer. Solicitation of several experts is frequently employed to try to develop a consensus estimate. Generally, such an exercise reveals considerable uncertainty.

It is our opinion that one should use the best data available and ascertain all the insight possible from the data base. For certain aspects of the analysis, for example solid rocket booster reliability, there would appear to be useful data. Where necessary, engineering judgment should be used. However, it is important to perform "sensitivity analyses" in such cases--that is, to vary the estimate over the range of opinion to ascertain the potential impact of the uncertainties on the results. Sensitivity analyses often reveal that particular judgments are important to the overall results. This insight aids the decision-maker and suggests areas for closer investigation.

- As a result of your studies, do you believe that additional work would be beneficial in this area in order to provide a more meaningful statistical calculation of failure probabilities? What additional work would you recommend, if any, that could further improve our estimation of the probabilities assigned to the failure modes?

There are a number of things that could improve our estimation of shuttle failure probabilities. First of all, the dominant failure mode to the mission involved failure of the solid rocket boosters. As noted above, there was a considerable difference in the estimates centering around whether or not solid rocket technology has improved with time. Our report developed a statistically sound approach for estimating the failure rate in the presence of learning. To apply this approach, we simply need more detailed information on the historical failures of solid rockets. From this could also come an estimate of the uncertainty, a subject addressed in neither report.

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The Wiggins' analysis was limited in scope to considering only "criticality 1" hardware failures. These generally involve only single hardware failures that can result in loss of the mission. Experience in analysis of other complex technologies suggests that common cause failures involving multiple pieces of equipment and human errors such as might arise during the assembly of the craft or in performing maintenance might be significant causes of failure. Expansion of the scope of the analysis to include these aspects would add credibility to the estimate and might uncover additional design weaknesses.

Finally, improvements could be made in the application of data. Where appropriate data exists, it should be used. When engineering judgments are made, the sensitivity of the results to such judgments should be examined.

A thorough review of these aspects of the assessment would not only improve our probability estimates, but it could also provide insights into areas of improvement for future design and operation.

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SUPPLEMENT TO THE RESPONSE TO THE QUESTIONS FROM
THE SUBCOMMITTEE ON ENERGY RESEARCH AND PRODUCTION

There are two basic questions relating to the manner in which failure rate probabilities are estimated.

1. Are historical data pertinent?
2. If historical data are used, what is the role of learning in the analysis?

Historical data refers to previous firings of solid rocket boosters (SRBs) for both manned and unmanned flights. For example, the data presented in Table 4.1 of the Sandia report originally appeared in the Wiggins' report labeled as relevant historical data. These data are repeated in Table 1. The data in Table 1 consist of firings of eight different types of SRBs. In particular, information is provided on 1324 first-stage firings and 556 second-stage firings for a total of 1880 firings. Wiggins indicated that 32 of these firings resulted in failures, with an additional 23 firings being suspect (these 23 are enclosed in parentheses in Table 1). Thus, the historical data provide a low-point estimate of the failure rate of 32/1880 = 1.7% per firing, and a high-point estimate of (32 + 23)/1880 = 2.9% per firing.

The concept of learning means that the reliability of a single system may improve through time as modifications are made to the system. Learning can also be applied across systems. Data taken over time within systems or across systems may indicate the presence of learning, no learning, or even dislearning (that is, increasing failure rates).

Table 1. Historical Data on SRB Failures

		FAILURES	
	LAUNCHES	1st STAGE	2nd STAGE
POLARIS			
A1	164	4(2)	8
A2	118	4(2)	1(4)
A3	203	2(3)	4
POSEIDON	67	0(4)	5(8)
TRIDENT	25	1	1
CASTOR II	600	1	-
CASTOR IV	36	1	-
TITAN	110	0	-

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The SRB failure rates provided in the Wiggins' report were not based on a statistical analysis of historical data, rather historical failure rates were heavily augmented with engineering judgment to provide an estimate of the failure rate. The concept of learning was not subjected to a statistical analysis in the Wiggins' report either. However, learning plays such an important role in guiding engineering judgment that it has become the central thrust of the Wiggins' work.

The approach taken by SERA utilizes a statistical analysis of historical data supplemented with current shuttle data. With respect to learning, SERA comments unfavorably on what Wiggins did, but they did not incorporate learning into their own analysis. In fact, if learning is present the SERA approach would lead to an overestimate of the failure rate.

The approach recommended in the Sandia report is that failure-rate estimates should have a statistical basis, use pertinent data, and be based on methods general enough to incorporate learning if present, ignore it if not present, or incorporate dislearning if the data indicate that to be the case. The approaches taken by each of these three groups is now discussed in some detail.

WIGGINS' APPROACH TO ASSESSING FAILURE RATES

In the second question from the subcommittee it is stated:

> "NASA has indicated that application of statistical analyses to shuttle failure modes would significantly overestimate the failure probabilities and, therefore, do not provide a realistic method for assigning probability values to various accident scenarios. They prefer to use engineering judgment."

The discussion that follows is intended to amplify the differences between an engineering approach and one based on the science of statistics.

In testimony given in the March 4, 1986, hearing on the Use of RTGs in Space Missions, Milton A. Silveira, Chief Engineer of NASA, offered an estimate of .00001 (1 in 100,000) of the failure rate for the SRBs on the space shuttle. This estimate was based on engineering judgment. Consider the implications of this estimate. Based on a failure rate of .00001 per SRB firing, the failure rate for the space shuttle is essentially .00002. This translates to an expected failure of 1 in 50,000 shuttle flights. Further, since this estimate is based on engineering judgment, there is no way to apply statistics to estimate how large the upper bound for the failure could be. The next paragraph examines the usefulness of determining an upper bound.

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The science of statistics provides a very reliable method of estimating failure rates if properly applied and interpreted. Consider the following example. Suppose that the data show 1000 successful launches. A statistical analysis of the data would show a point estimate of zero for the failure rate, but would also provide an upper 5% bound for the failure rate of .003. If someone were to interpret this upper bound as being the point estimate of the failure rate determined by statistics, that interpretation would be incorrect. The correct interpretation of this bound is that a failure rate as high as .003 is entirely consistent with the observed data. That is, even with a failure rate as high as .003, it is still likely to observe no failures in 1000 launches. Further, is someone were to say that "this bound means that during the next 1000 launches there will be three failures," that too, would be an incorrect interpretation. In truth, this number does not carry any implications about the number of failures in the next 1000 launches; there could be 0 failures, 1 failure, 2 failures, 3 failures, or more during the next 1000 flights.

As mentioned previously, the historical data show a failure rate of either .017 or .029 per firing. These numbers are entirely in line with the 2% failure rate observed on the space shuttle. In contrast, the Wiggins' report indicates that these historical numbers were lowered to .001 by the Space Shuttle Range Safety Ad Hoc Committee on the basis that improvement in solid rocket motor technology over time had resulted in lower failure rates. It is important to point out that the historical rates were based on flights of about 60 seconds in duration, while the shuttle SRB firings are of about 126 seconds duration which may mean that the failure rate is actually higher than that which the historical data indicate. This revised estimate was further reduced to .0001 by the range safety committee because of the dominance of VRM-2 and the high degree of uncertainty in the failure probability estimate (SERA, page 31, criticized the Wiggins' report for disregarding the historical data and for the arbitrary assignment of risk levels apparently per sponsor direction). Apparently this number has been adjusted still lower to .00001 according to the March 4, 1986, testimony of Silveira. It is also worth noting that uncertainty estimates were provided for other parts of the risk analysis not involving SRBs, that is, some statement of how low or how high the failure rates might be. In contrast, the most dominant failure rate (the SRBs), with an admitted high degree of uncertainty, consists of a single-point estimate without an associated statement of uncertainty.

Since estimates based on the historical data in Table 1 are entirely in line with observed shuttle SRB data of 1 failure in 50 firings, it would seem that historical data could have a role to play in the establishment of an appropriate data base. Further, such a data base should be used to develop a statistical technique for estimating the failure rate, complete with a statement of uncertainty.

SERA's APPROACH TO ASSESSING FAILURE RATES

SERA's approach to estimating the failure rate of the SRBs on the space shuttle consists of two steps:

1. Describe the historical data on SRB failure rates with a probability distribution (this is referred to as the prior distribution).

2. Update the prior distribution with data on actual space shuttle flights to create a new probability distribution for the failure rate (this is referred to as the posterior distribution).

While this approach has a sound philosophical basis, the technical execution of the procedure by SERA was flawed. In addition the SERA approach failed to incorporate learning into the analysis. Without being burdensome with too many technical details, the SERA analysis can be summarized as follows.

1. Recall that the historical data in Table 1 yielded an estimated failure rate of .017 when suspected failures are not counted and a failure rate of .029 when suspected failures are counted. SERA chose to describe these historical data with a lognormal prior probability distribution having a mean of .0218. The mean of this lognormal is close to the geometric mean of the historical rates; that is $(.017 \times .029)^{1/2} = .0222$, so the lognormal distribution represents a reasonable choice in terms of its mean. However, the lognormal distribution itself does not properly describe the historical data. To illustrate this point consider the cumulative distribution function of the lognormal distribution used by SERA that is represented as the smooth curve in Figure 1. The historical data also appear in Figure 1 in the form of empirical distribution functions. The historical data with a mean of .017 appear as a step function with solid lines, while the historical data with a mean of .029 appear as a step function with dashed lines. Clearly, the lognormal distribution assumed by SERA is not appropriate for these data. SERA does qualify the selection of the prior distribution (see page 35 of the SERA report), but it is this distribution that was used to produce the 1 in 35 failure rate that has been widely quoted and attributed to the SERA study.

2. Next SERA chose to use a discrete representation of the lognormal prior (see Table 4.2 in the SERA report). The discretization was not necessary and was done incorrectly. The discretizing of the lognormal distribution gives a close representation of the distribution as shown in Figure 2; however, it has an adverse effect on the mean, which is changed from the intended value of .0218 cited in comment (1) to a value of .0177. Even if the discretization had been done correctly, the mean would still be lowered to .0193. This simply points out the inappro-

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FIGURE 1. LOGNORMAL PRIOR AND HISTORICAL DATA

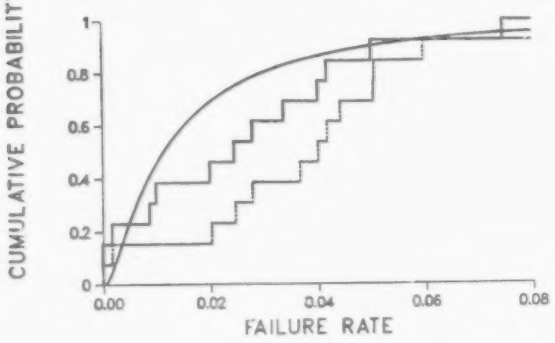
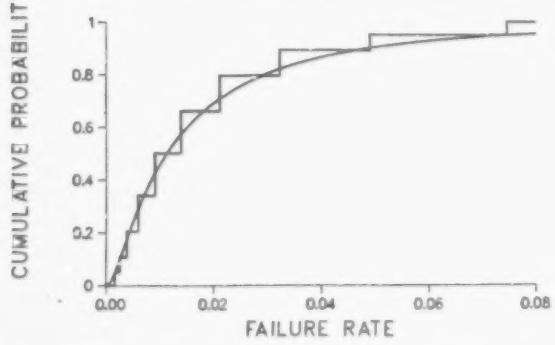


FIGURE 2. LOGNORMAL PRIOR AND DISCRETIZED LOGNORMAL



priateness of using a discrete representation of the prior distribution. This may seem like a minor point at the present time, but as pointed out in the next comment, discretizing the lognormal has an adverse effect on the estimates arising from using this approach.

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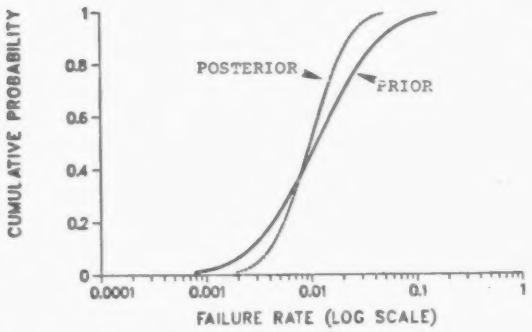
FIGURE 3. LOGNORMAL PRIOR AND POSTERIOR DISTRIBUTIONS (80% BOUNDS)

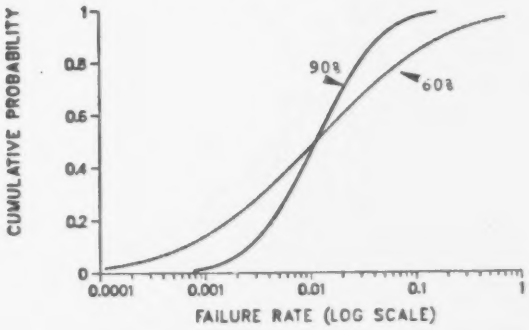


3. SERA uses a Bayesian approach to update the historical data with data based on the first seven shuttle flights (no failures in 14 SRB firings). The corresponding analysis (see page 36 in the SERA report) produces a posterior distribution having a mean failure rate of .0141 per SRB firing, or 2 x .0141 = .0282 per shuttle launch. This is the source for the quoted number of 1/.0282 = 35.5 or 1 in 35 chance of failure. Further, SERA incorrectly assumes that the posterior distribution is lognormal with an upper 5% bound of .0311. The posterior distribution is not lognormal, nor is the upper 5% bound of their posterior distribution .0311, rather this value is closer to a 13% upper bound (see page 42 of the Sandia report). Graphs of the cumulative distribution functions of the prior and posterior distributions assumed by SERA appear in Figure 3.

   While the estimate of .0141 produced by the SERA approach may seem reasonable, it is much easier to see the technical problems with the SERA approach when it used to update the historical data with the current shuttle data of 1 failure in 50 SRB firings. This analysis produces a posterior mean of .0173 per SRB firing. To understand the problem with this number, recall that SERA starts with a prior distribution having a mean of .0218 and updates it with data having a mean of .02. Common sense tells one that the mean of the posterior distribution must be at least .02. Even if one allows for the mean of the discretized version of the lognormal distribution, which was .0177, the results still do not make sense. SERA's errors have compounded at this point, but center for the most part on the unnecessary and improper discretization of the prior distribution mentioned in comment (2).

4. SERA (see page 34 of the SERA report) derived its prior distribution discussed under comment (1) by assuming that the Castor

FIGURE 4. PRIORS DERIVED FROM 60% AND 90% BOUNDS



data (see Table 1) of 1 failure in 600 trials represented the .05 quantile of a lognormal distribution, and that the Poseidon second-stage data (see Table 1) of 5 failures in 67 trials represented the .95 quantile of a lognormal distribution. These assumptions correspond to the .95 - .05 = .90 or 90% confidence limit interpretation of the historical failure rate data.

SERA offers a second analysis in which the interpretation is changed such that the rate of 1 in 600 represents the .20 quantile of a lognormal and the rate of 5 in 67 represents the .80 quantile of a lognormal. These assumptions correspond to the .80 - .20 = .60 or 60% confidence limit interpretation of the historical failure rate data.

The graphs of the cumulative distribution functions of the priors based on the 90% and 60% interpretations are shown in Figure 4. As can be seen in Figure 4, the 60% interpretation has a much greater spread associated with the failure rate distribution. This is equivalent to saying that there is greater uncertainty associated with the failure rate. The 60% interpretation also increases the mean of the prior failure rate distribution by more than a factor of 6 from .0218 to .1397. Since this latter value is twice the upper limit of .0746 used to define the distributions, it can have a tremendous impact on the failure rate estimate. For example, the mean of .0218 based on the 90% interpretation translates to a failure rate of 1/.0436 = 22.9, or 1 chance in 23 of failure for the shuttle. The mean of .1397 based on the 60% interpretation translates to a failure rate of 1/.2794 = 3.6, or 1 chance in 4 of failure for the shuttle.

The graphs of the cumulative distribution functions for the prior and posterior distributions based on the 60% interpreta-

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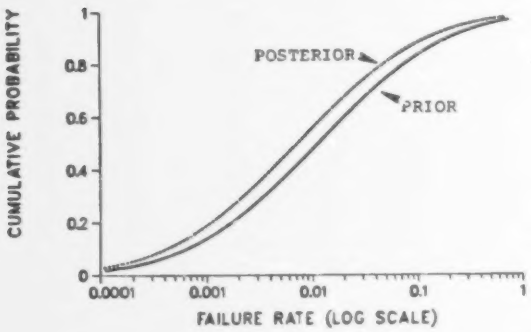
FIGURE 5. LOGNORMAL PRIOR AND POSTERIOR DISTRIBUTIONS (60% BOUNDS)



tion appear in Figure 5. Figure 5 can be compared directly with Figure 3 to more clearly see the impact of the 60% interpretation versus the 90% interpretation.

As stated in the Sandia report, SERA did not make a prima facie case for the use of 60% bounds.

THE APPROACH RECOMMENDED IN THE SANDIA REPORT

As stated in the March 4, 1986, testimony given by David Carlson, Sandia developed a methodology for assessing the failure rate of the SRBs but did not produce an estimate as it was not possible to obtain the necessary data, although such data appear to exist.

This methodology is explained in Section 4.2.4 and Appendix A of the Sandia report. It is also explained further in the enclosed report (3 copies) entitled "Bayesian Analysis of Learning." In the absence of the actual data, the report resorted to the use of artificial data that was designed to fully exercise and demonstrate the methodology.

The methodology is based on Bayesian statistics and requires that a time history be available on the historical data. That is, the historical data in Table 1 does not appear with dates. The time history is needed to see if improvements have historically taken place within systems or from system to system. As illustrated in Table 9 and Figures 1 to 10 of the attached report, the methodology incorporates learning if it is present, ignores this aspect if learning is not present, and incorporates dislearning if it is present. Figures 6 to 9 in this response illustrate the variety of forms in which historical data could appear and be incorporated into the methodology.

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FIGURE 6. WELL-DEFINED LEARNING

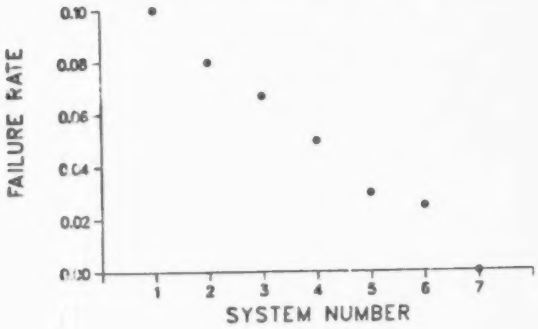

FIGURE 7. CONSTANT FAILURE RATE

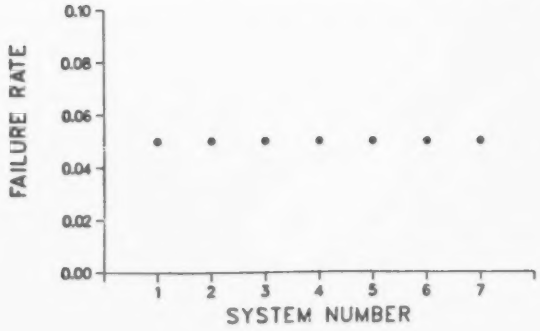

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FIGURE 8. RANDOM LEARNING

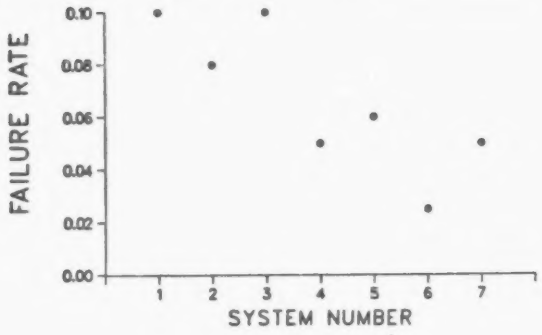
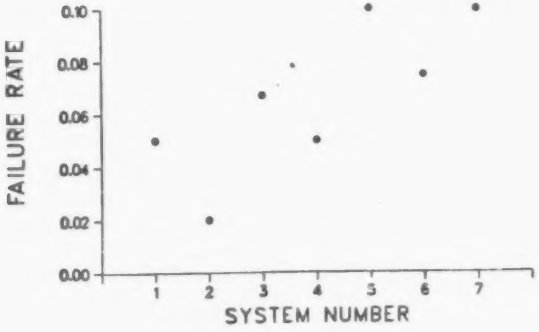


FIGURE 9. RANDOM DISLEARNING



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APR 07 RECD

March 31, 1986

Refer to: 230-JRC:gt-027

Marilyn Lloyd, Chairman
Subcommittee on Energy Research
and Production
Suite 2321 Rayburn House Office Building
Washington, DC 20515

Dear Madam Chairman:

I am pleased to provide the enclosed answers to the additional questions, and would like to thank both subcommittees for giving us the opportunity to testify.

You will find that the answer to the question on the application of statistical analyses and the existence of meaningful database to be rather lengthy. I am sorry for that, but the issue was not clearly understood at the testimony and a fuller treatment seems warranted. I hope that my efforts contribute a little bit in that respect.

I will be pleased to provide additional information should you desire.

After the testimony, I was told that witnesses are normally expected to submit a brief biography along with their written testimony. One is included herewith.

Sincerely,

John Casani

John R. Casani
Project Galileo Manager

Enclosures

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ANSWERS TO QUESTIONS FROM CHAIRMAN MARILYN LLOYD

Question:

What is the nature of the analysis used to select power sources for specific missions?

Answer:

Power sources for planetary missions are selected on the basis of tradeoff studies to determine the source that best meets the system's requirements. These requirements include power output, spacecraft mass, reliability, scientific objectives, environments, cost, safety, and maturity of the required technology. Power sources typically considered are solar panels (photovoltaics), batteries, and nuclear (radioisotope thermoelectric generators and reactors). The tradeoff study evaluates the use of a particular power source in a design analysis that considers the integration of the power source with the remainder of the power regulating and distribution equipment, i.e., a power subsystem and the integration of that subsystem with the total system. The system design using the power source is then evaluated as to performance relative to the above requirements and attendant uncertainty (e.g., relative to maturity of the required technology). The performance of system designs using different power sources are then compared and the source selected based upon this comparison.

Question:

Clearly, the Challenger accident has impacted the flight schedule for the Galileo Mission. How do the postponements of these launches of Galileo and the Ulysses affect these missions?

Answer:

The postponement of these two launches will affect the missions in several ways. Aside from the delay of the science data return and the disruption to the careers of the hundreds of scientists and engineers working on them, many in mid career, the main effect will be to increase the cost of the missions. Cost increases will arise from the efforts associated with the redesign of the missions, the storage of the spacecraft and the retention of critical skills needed for launch operations.

Question:

Can either mission be launched on an expendable vehicle such as the European Space Agency's Ariane or an Air Force Titan?

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Answer:

Neither mission can be launched on the Ariane or on any other currently available expendable launch vehicle. Use of the Air Force CELV is a possibility, but only with the addition of auxiliary stages. For the Ulysses Mission, a kick stage must be used to provide the total velocity required. For Galileo, only delta VEGA trajectories could be flown using the CELV. The auxiliary stage in this case would be a deep-space delta VEGA stage to provide the required deep-space velocity. This type of stage is not required for delta VEGA trajectories when the Shuttle Centaur is used.

Question:

What other flight options are available presuming that Galileo certainly will not be launched before 1987?

Answer:

Direct trajectory launch opportunities for Jupiter occur approximately every 13 months. Thus, there is another launch period in June-July 1987, one in August 1988, one in September 1989 and so on. In addition to the direct trajectories, there is another type of trajectory known as delta VEGA. Delta VEGA trajectories generally require less energy from the launch vehicle at the expense of longer trip times. For Galileo, the trip time to Jupiter increases from 2-1/2 years to 4-1/2 years. Delta VEGA launch opportunities also occur every thirteen months, but occur later in the year than the direct trajectories. For example, there is a delta VEGA period in December 1987, another in January 1989, and so on. In passing, it should be noted that the Ulysses spacecraft does not have the propulsive capability to perform the deep-space maneuver required for delta VEGA trajectories.

Question:

What unique safety precautions are taken before launching spacecraft that carry RTG's?

Answer:

In my prepared testimony I have described precautions taken to provide for personnel and equipment safety in the normal flow of activities prior to launch. I assume this question is directed to safety in the event of a launch vehicle accident and will construct my answer accordingly. The unique safety precautions, that I am aware of, that were or are intended to be taken before launching RTG's are:

(1) On the Voyager spacecraft, a mechanical device was added to the design at the RTG interface such that, in the event of spacecraft reentry into the Earth's atmosphere, the attendant heating would cause the device to release the three RTG's to

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enter individually rather than as three attached units. This was done because the aerodynamic characteristics of individual RTG's were better (safer response) than that of the three RTG's tied together.

(2) The Galileo daily launch window was selected to be during daylight versus night to permit better viewing for Range Safety personnel.

(3) Wind velocity and direction is being considered as a launch commit criteria so that, in the event of nuclear fuel release in a launch accident, the likelihood of dispersion over populated areas is reduced.

(4) See also the response to the question regarding activities that take place before launch at the site that the committee should be aware of.

Question:

Do you perform any additional analyses beyond that which has been discussed today as relates to the Department of Energy's responsibilities and the INSRP responsibilities?

Answer:

In the event of an accident that would result in the spacecraft reentering the earth's atmosphere, the spacecraft will break up due to the aerodynamic forces acting on it and eventually the outer shell of the RTG's will fail releasing the eighteen heat source modules. Each individual module is designed to survive reentry and to contain the fuel upon impact. JPL performs the analysis which describes the spacecraft breakup and defines the relevant initial conditions for the RTG heat source modules at the time of release from the spacecraft. This information is used by the DOE in their analysis of the response of the modules to reentry and subsequent impact.

Question:

As Payload Project Manager, are there any activities that take place before launch at the site that the committee should be aware of as it relates to RTG safety?

Answer:

Representatives of the KSC Safety Office are actively pursuing contingency planning relative to radiological safety in the event an accident causes radioisotope release at the Kennedy Space Center, off the Kennedy Space Center, or at a contingency landing site. Their effort deals with other federal, state, and local agencies and is following the Federal Radiological Emergency Response Plan (dated November 8, 1985). During the launch countdown, an emergency control center, called

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the Radiation Control Center (RADCC), is manned by KSC and DOE. It has communication capability with local and other agencies and would serve to coordinate the activities of emergency personnel in the event of an accident causing a radioisotope release on or off Kennedy Space Center.

Question:

As Project Manager for these flights, what role do you play in the Department's deliberations as to the safety of these RTG devices?

Answer:

As Project Manager for Galileo I play a role in the management of the process by which data flows to DOE from JSC and JPL, and an oversight role in the review of status and results of the safety analysis. I do not play a direct role in DOE's deliberation as to the safety of these RTG devices.

Question:

Do you anticipate that as a result of the Challenger accident and the related mission delay of at least 13 months, that additional safety research could be performed that would benefit the flight program?

Answer:

As I mentioned at the hearing, we intend to perform additional design studies and possibly development testing to assess whether a form of shield or other protective device could be employed which would improve the nuclear safety risk assessment without unduly increasing the overall risk to the programs. Additional thoughts are included in the response to the last question below.

Question:

NASA has indicated that application of statistical analyses to shuttle failure modes would significantly overestimate the failure probabilities and, therefore, do not provide a realistic method for assigning probability values to various accident scenarios. They prefer to use engineering judgment. Do you believe that an adequate database could be established or does an adequate database exist, which would permit a meaningful statistical analysis of shuttle failure rates and accident scenarios?

Answer:

I do not believe that an adequate database exists, nor do I believe that one could be established, which could permit a meaningful statistical analysis of Shuttle failure rates and accident scenarios.

Let me explain why. The classical approach to reliability analysis of a complex system attempts to characterize each and every component of the system with a failure rate. The failure rate is expressed as the number of

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times that the part or component in question may be expected to fail in a given period of time. It is usually expressed as a percentage number of part failures per thousand hours of operation. For example, the failure rate for high-rel transistors of certain types might be expressed as .01% per 1000 hours. Different transistor types typically have different failure rates. These failure rates are derived from a statistical analysis of the reported numbers of failures of the particular transistor type during a life test program or during actual field use of the equipment containing the transistor. Typically, hundreds or even thousands of transistors each with hundreds or thousands of hours would form the database for this calculation. For the statistical analysis to be significant, the database must include a large number of samples, just as an opinion poll must sample a reasonably large number of people in order to produce statistically significant results.

Frequently, in the case of transistors, and many other types of components as well, the failure rates will be determined only for one or two specific transistor types. The calculated rates will then be conferred onto other component types having similar characteristics.

In some cases, when a reliability analyst has to calculate the reliability of a system containing a component for which there is no published failure rate data, he will search the literature for components with published data attempting to find one having design and performance characteristics similar to the component in question. Using that failure rate as a point of departure and by forming a judgment based on the similarities of function and design he will assign a failure rate to the component in question.

Clearly, in the case of the Shuttle the large majority of components, especially in the propulsion system, are one of a kind design. Each design is exhaustively analysed and tested by NASA in the development phase. Because only a relatively few number of components are manufactured, there is not a statistically large number of samples available, so the database is small to begin with. The NASA approach requires that whenever a failure does occur, no matter when it occurs in the development cycle and no matter how small or insignificant it is, the cause of the failure must be determined and corrective action must be taken. Corrective action must be taken not only on the failed item, but on all items of the same kind. In fact, any other item or system employing a design similar to the one which failed must be reviewed to determine whether corrective action should be applied there, too. The effect of this policy, and this is the is the key point, is that it destroys the statistical significance of the database as applied to that failure mode. This is true, since once the cause of the failure has been corrected, there is no information for predicting failures in the future based on that type of failure mechanism.

To continue with the analogy, suppose the transistor manufacturer were to determine the cause of each and every failure reported from the database and to introduce corrective measures in the design and/or fabrication processes that would preclude each of those failures from recurring. Then in terms of assigning failure rates to new transistors, the original database would be useless. This is the reason NASA does not use probabilistic risk assessment techniques. NASA belives that this type of analysis is useful for

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predicting the statistical behavior of a large number of systems built from standard components whose failure rates have been reasonably characterized by life test or field use data from a statistically large number of samples. This technique would be useful, for example, in predicting how many (out of say 10,000) Jeep radios manufactured using standard components could be expected to fail in a period of five years, or what the probability of failure of a single radio would be in some period of time. The underlying assumption in this type of analysis is that the failure rates are known, that the failures occur randomly in time, and roughly at a constant rate. This is a useful modeling technique and it does a pretty fair job of predicting real life situations when the model assumptions are valid. NASA philosophy holds that failures occur for a cause, and if the cause can be found, a way to prevent future failures due to that cause can be implemented.

Take the seal failure as an example. Once the cause is found and corrected, no one should expect the seals to fail again, at least not for the same reason. By the same token the STS database, reflecting one seal failure in 25 flights has no significance in predicting what the new failure rate will be. Only if NASA were to continue flying without making any changes in the design and without imposing any new launch constraints, on weather for instance, would the existing database be useful.

In closing, probability risk assessment (PRA) techniques are frequently used to good advantage for comparison of alternate ways to solve a problem. However, care must be taken to properly use the database in arriving at statistically derived failure rates. PRA's rarely yield usable or believeable estimates of absolute reliability. Further, their application to very large systems, consisting of hundreds of thousands of components is extremely cumbersome and costly. In the case of the Shuttle, and indeed, most all NASA hardware, the infeasibility of creating a meaningful database, in my opinion, renders the approach totally ineffective for quantative reliability estimation.

Question:

Are there other experiments or tests on RTG safety features, in addition to the liquid hydrogen/oxygen explosion tests you mentioned in your testimony before the subcommittee, that you would recommend be undertaken by the DOE?

Answer:

One of the major uncertainties in the present FSAR has to do with the quantity of fuel released following an impact of the RTG clads with the structural elements of the Orbiter. The DOE has conducted clad impact tests with steel, concrete, and sand. The FSAR uses the data from the concrete impact tests to predict fuel release resulting from RTG clad impact with Orbiter structure. We believe that this approach leads to unrealistically high releases and that the DOE should conduct impact tests with representative simulations of the orbiter structure.

As I mentioned in my testimony, there is wide disagreement in the community on the proper interpretation of the Project Pyro database in terms of

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deriving from it an estimate of the environment to be expected in the immediate vicinity of a hypothetical Centaur explosion. I suggested that a test program could be run to better understand the characteristics of liquid hydrogen/oxygen mixing and combustion processes. The community is largely in agreement that this sort of testing is necessary.

Other approaches are possible. The DOE should consider a test program which would allow correlations between hydrogen/oxygen explosion environments and environments created by high explosive charges. Tests of this sort have been suggested as a way providing information which will allow consistent interpretations of Pyro data and as a way of testing the RTG components in representative environments without having to set off hydrogen/oxygen explosions.

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BIOGRAPHY OF JOHN R. CASANI

John R. Casani is Manager of the Galileo Project at JPL.

Before that, Casani was Manager of the Voyager Project; he was appointed to that position in April 1976. He is former Manager, Guidance and Control Division, Jet Propulsion Laboratory, California Institute of Technology.

Before serving in these posts, Casani was the Spacecraft System Manager for the Mariner 1973 Venus-Mercury Project (Mariner 10). He held similar key engineering positions on JPL's space flight projects, beginning with Explorer 1. He worked on the early Pioneers, Rangers, and Mariners, the first probes of the Moon and planets.

In 1965, the National Aeronautics and Space Administration honored him with an Exceptional Service Medal "for significant engineering achievements contribution to the Mariner IV Mission to Mars". He also received the Pasadena Chamber of Commerce Distinguished Service Award in 1965.

In 1973, he received a Distinguished Alumni Gold Medal Award from the Moore School of the University of Pennsylvania for "significant advances in the design of spacecraft systems and their management during specific missions . . . ."

In 1974, Casani was again honored with NASA's Outstanding Leadership Medal for his "leadership as Spacecraft System Manager of the Mariner Venus-Mercury 1973 Project".

In 1979, Casani was the recipient of the American Institute of Aeronautics and Astronautics Space System Award, and in 1980 he was installed as a Fellow of that organization.

In 1981, Casani was the recipient of the National Space Club's Astronautics Engineer Award for his "outstanding direction of the Voyager Project".

Also in 1981, Casani was the recipient of NASA's Outstanding Leadership Medal for his "contributions as Voyager Project Manager".

Casani was born September 17, 1932, in Philadelphia. He graduated from the University of Pennsylvania in 1955, with a bachelor's degree in electrical engineering, and joined JPL in 1956 to work on inertial guidance systems for guided missiles.

He is married, lives in Pasadena, and has four children.

NUS CORPORATION
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GAITHERSBURG, MARYLAND 20878-1399
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March 28, 1986

APR 02 1986

The Honorable Marilyn Lloyd
Chairman, Subcommittee on Energy Research and Production
U.S. House of Representatives
Suite 2321 Rayburn House Office Building
Washington, DC 20515

Dear Representative Lloyd:

Enclosed with this letter are the responses to the questions sent with your letter of March 19, 1986 to Mr. Roy Denham. Since the questions related to my testimony, Mr. Denham asked me to respond for him.

Very truly yours,

Richard W. Englehart, PhD.
Senior Executive Consultant

Enclosure

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QUESTION 1

I wonder if you could just explain for the Committee again in layman's terms when you talk about cancer deaths, say for example, in the particular accident scenario, is that the actual number of people that will die should an accident occur. Just what do those numbers really mean in terms of the actual risks to individuals?

ANSWER

Should an accident occur, the consequences would be determined by the actual conditions existing at that time and by protective and remedial actions taken subsequently. For example, if a launch pad accident were to occur and the wind was blowing offshore as it was during the Challanger launch, then any radioactive material released would not be inhaled by people in the launch area. Some population dose would result if consumption of contaminated seafood were allowed, but the calculated cancer deaths would be much lower than expressed in the FSAR.

When cancer deaths are calculated from a population dose, especially at low dose levels, they should be interpreted to be the upper limit of a range of potential cancer deaths, the range including zero (no cancer deaths) as a possible result.

The purpose of the risk calculations, which involve the quantification of potential cancer deaths, is to provide input to the decision making process. There is about a 0.008 percent chance (or one chance in 12,500) that an accident may occur which could result in between about 0 to 40 cancer deaths over a period of about 50 years in a population of about 100,000 persons

On the other hand the probability approaches 100 percent* that in the same 100,000 person population over that 50 year period death statistics will look like:

1500	will die in motor vehicle accidents
450	will die in falls
200	will die in fires
150	will die by poisoning
50	will die by shooting
50	will die in machinery accidents
45	will die in boating accidents
45	will die in air travel accidents
30	will die by being hit by falling objects
30	will die by electrocution
200	will die in other miscellaneous accidents
40,000	will die from diseases (including about 8,000 cancer deaths from other causes)

*Improvements over the years in safety standards and in cancer cures might change these predictions for the better.

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To summarize, the FSAR estimates that there is about a one in 12,500 chance that somewhere between 0 and 40 people in 100,000 persons may develop a fatal cancer due to a launch accident over a 50 year period if the mission is attempted. In the same population the probability is about one that about 3000 will die by accident, 8000 will die of cancer, and 32,000 will die of other diseases over 50 years. Thus, the added risk to an individual is extremely small compared to other risks. Even if an accident actually occurred, the risk to an individual of a fatal cancer because of the accident would be comparable to the risk of death by being hit by a falling object.

QUESTION 2

You have a table which shows, based upon 1969 population figures, the level of risks that an individual faces in terms of fatalities per year for a host of maladies that can affect the population ranging from automobile accidents to disease and infection. On the other hand, you compare that to the risks that an individual would be exposed to from the flight of the Galileo or Ulysses missions. It appears that the added risks as a result of these missions is negligible compared to some of these more understood dangers facing mankind. Is that correct?

ANSWER

That is correct, as discussed in the answer to Question 1. It is intended that the mission risks to an individual be directly compared to the 1969 population risk figures in order to gain perspective. The risks to the launch area population are smaller than any number on the 1969 table.

QUESTION 3

Let's take your worse case scenario. If this worse case accident were to occur, for example, an explosion of a centaur that released the maximum amount of radioactive material as in Phase 3, or the orbiting phase, of the Galileo or Ulysses flight, would we really be exposing the world population to hundreds of thousands cancer deaths?

ANSWER

No. Even if one accepts the upper limit FSAR quantification, it is about 2500 in about 4 billion people, of which upwards of 1 billion will die of cancer from other causes.

Beyond this, however, there is a real question as to the usefulness of such numbers since they are calculated to result from doses on the order of one percent of background radiation. When doses are in the range where the ordinary citizen does not consider them in their decisions (such as what style of house to live in or in what part of the country to live, or whether to take an airline flight) then it does not make sense to consider them in a risk assessment. If one accepts this criterion and discounts radiation doses less than one millirem per year, then there would be no cancer deaths attributable to accidents in mission Phases 2, 3, and 4.

all about it

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[redacted]

10 April 1986

Refer to: TES-PJV-220

[redacted]

The Honorable Bill Nelson
Chairman
Subcommittee on Space Science and Applications
Suite 2321
Rayburn House Office Building
Washington, DC 20515

Dear Congressman Nelson:

At your subcommittee hearings on 4 March on "RTG Utilization in Space Missions," you requested our comments on the Sandia Report SAND84-1579 which critiqued our Air Force Weapons Lab-sponsored report entitled "Review of Shuttle/Centaur Failure Probability Estimates for Space Nuclear Mission Applications." We are pleased to forward to you our comments in the enclosed report. It was prepared by Denton C. Anderson who assisted me in answering your questions at the hearings, with the participation and agreement of our original report authors, Mr. R. K. Weatherwax and Dr. E. W. Colglazier, representing Sierra Energy & Risk Assessment, Inc., our subcontractor for the AFWL study.

In order to adequately address the Sandia critique issues, our comments are necessarily technical and extensive. We will be happy to assist you or your staff to interpret the report if you so request.

We appreciate the opportunity to submit these comments and to contribute to your hearings on the use and safety of RTG's for space missions.

Sincerely,

Peter J. Vogelberger, Jr.

cc: Mr. Nelson L. Milder
Subcommittee on Energy Research & Production

Dr. David D. Carlson
Sandia National Laboratory

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[redacted] OF SANDIA REPORT [redacted]-1579

1. INTRODUCTION

A sequence of reliability studies of the Space Transportation System was completed recently. The first study, by Drs. J. Baeker and J. Hudson (Ref. 1-3) then of the J. H. Wiggins Co., was sponsored by NASA. It was initially directed toward range safety considerations, but was redirected to develop reliability data to be used as ingredients for nuclear safety analyses of the Galileo and Ulysses missions.

Baeker and Hudson's work was reviewed by Mr. R. K. Weatherwax and Dr. E.W. Colglazier[1] of Sierra Energy and Risk Assessment (SERA), Inc., who were sponsored by Teledyne Energy Systems (TES), under contract to the Air Force Weapons Laboratory (AFWL). The purpose of the SERA review was to assess the aptness and applicability of the Wiggins-derived vehicle failure rates for nuclear risk analyses. SERA's review was reported in Ref. 4.

Owing to substantial differences in failure rate estimates by the two sets of investigators, a second review was commissioned by the AFWL. This second review was performed by Drs. Carlson, Hatch, Iman and Nora of the Sandia National Laboratories. The Sandia report (Ref. 5) was issued in December, 1984, and recently became available to TES and SERA. The Sandia review found weaknesses in each of the prior studies, but did not offer quantitative estimates for critical failure rates.

Congressman Nelson of Florida, who gave Messers. Vogelberger and Anderson of TES a copy of the Sandia report during a hearing on space utilization of RTGs on March 4, 1986, requested that TES review the report and evaluate it. This report was prepared to present our response to Congressman Nelson's request.It reflects the opinions of both TES and SERA.

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[1]Currently at the University of Tennessee.

Issues considered by Sandia were separated into three topical areas: failure probability estimates for the solid rockets boosters (SRB), failure rates for vehicle failure modes other than those related to SRB failures, and other basic methodological issues. Our response addresses each of these issues in turn in Sections 2 to 4. The final section summarizes our conclusions.

2. SRB FAILURE PROBABILITY

The SRB burn-through failure mode represents the complete contribution to Vehicle Response Mode (VRM) number 2, "loss of control and tumble," as referred to in the several reports. Wiggins presented historical data from launch attempts and burn-through failures for several different types of solid rocket motors in Table 3-7 of Ref. 1. These Wiggins data show 32[2] confirmed failures and an additional 23 suspected failures from case or nozzle burn-through out of a launch data base consisting of 1902 motors launched. From these data, Wiggins computed an average probability of failure of about 1/57 (0.0175) when only the confirmed failures were considered. However, the report recommended using failure frequencies of either 0.001 or 0.0001 to reflect unidentified reliability improvements resulting from the prior experience and man-rated systems.

SERA, in its review, concluded that there was no evidence of learning offered by Wiggins. Therefore all experience should be used to predict failure frequency. To incorporate the history of the prior experience, SERA used a Bayesian procedure to predict the distribution of SRB failure probability. A lognormal distribution was assumed and the average performance levels of the Castor II and Poseidon second stage (the two missiles with, respectively, the best and worst observed failure rates for burn-through) were selected to represent the extrema of the prior distribution. This prior distribution was combined with Shuttle experience at that time (7 successful launches) to derive a posterior distribution. The results showed a mean failure probability per motor per launch of 0.014. The 90% interval range, if a log-normally distributed posterior was assumed, was from 0.0031 to 0.0311 if the prior extrema were assumed to represent a 90% range.

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[2]Wiggins reports a total of 33 confirmed failures but only presents data showing 32 confirmed failures.

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Sandia pointed out four perceived weaknesses in the SERA modeling:

1. Using a prior distribution that implies no learning;
2. Selection of a lognormal prior derived from only two of the data values rather than using standard statistical procedures;
3. Errors in two values of the discretized approximation; and
4. Assumption of a lognormally distributed posterior.

Among these points, the first is potentially the most significant. Sandia criticized the SERA analysis because SERA used unweighted historical data without providing for learning or improvement and further, that omission of learning produced an upward bias in the estimate of SRM failure probability. Later (Ref. 5, p. 45) it is stated that a more complete history of SRB failures would allow improved estimates of the Shuttles's SRB reliability, i.e. by including learning in the estimation process.

However, Sandia presents a plot (Figure 4-9) in which mean failure probabilities for the different SRMs making up the data base are shown approximately as a function of time when the motors were being produced and launched. The display does not include three points: Titan, Poseidon second stage and Trident second stage failure data. With or without these points, however, the data are well scattered and suggest no trend. Sandia, at this point concludes: ".....there is no well-defined learning curve apparent in Figure 4-9," and, of course, we agree.

Secondly, Sandia's conclusion that omission of learning in SERAs model produces an upward bias in its estimate presumes that a more detailed analysis would show reliability improvement rather than the other possibilities presented later (p. 46) of no improvement or even degradation.

Finally, if more detailed historical data were reviewed and did indicate a trend toward improvement with time within individual subsets of data, it isn't clear what the implications of these data would be for the Shuttle SRBs. Would one conclude, for example, that initial reliability would be low, but that eventually it would improve?

In a practical sense, we see no evidence of reliability improvement with time for new motor designs. Further, if a data trend were apparent it would make sense to relate that trend to physical changes in hardware or procedures. If there were no changes, the apparent trend would likely be a random fluctuation.

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Sandia's remaining three criticisms apply to SERA modeling of the historical data and imprecisions in the calculations. We agree with these criticisms; however, the salient point is that historical data suggest a probability that is much more likely to be about 0.01 than 0.001 or smaller as reported by Wiggins. So that this point is documented firmly, we present results using updated models in which:

a. prior distributions are derived from the detailed data sets for individual motor classes;

b. the discretized method of numerical integration is replaced by a more analytic method; and

c. posterior distributions are calculated directly rather than depending on lognormal representation.

Therefore the updated models address each of the final three criticisms made by Sandia, related to SRBs.

Figure 1 shows a lognormal plot of mean failure rates for the several classes of SRMs and three Bayesian prior distributions which will be compared. The data points are actually Bayesian means and their derivation is given in Appendix A. The three priors considered are: (1) a SERA's lognormal, (2) a lognormal derived from the data points and (3) a binomial distribution derived from a uniform prior and no failures in twenty-one attempts. The last prior has no physical basis; it happens to fit the data points very well.

Posterior distributions derived from the foregoing priors and the data set of 14 motors launched without failure used by SERA, are shown in Figure 2. Methods for calculating the distributions are given in Appendix B. The posteriors show the strong dependence on the assumed priors and, in fact, the posteriors approach the priors asymptotically with decreasing failure probability, owing to the binomial representation of Shuttle data.

Statistics of the three distributions shown in Figure 2 are presented in Table 1. Comparison of the SERA data in the first column with the analytic calculation using SERA's lognormal can be done to evaluate the effects of items 3 and 4 among Sandia's criticisms. The total effect of these items is seen to be relatively small, with the largest deviation being a factor of two between the 0.05 fractile values, owing primarily to SERAs lognormal extrapolation (Item 4).

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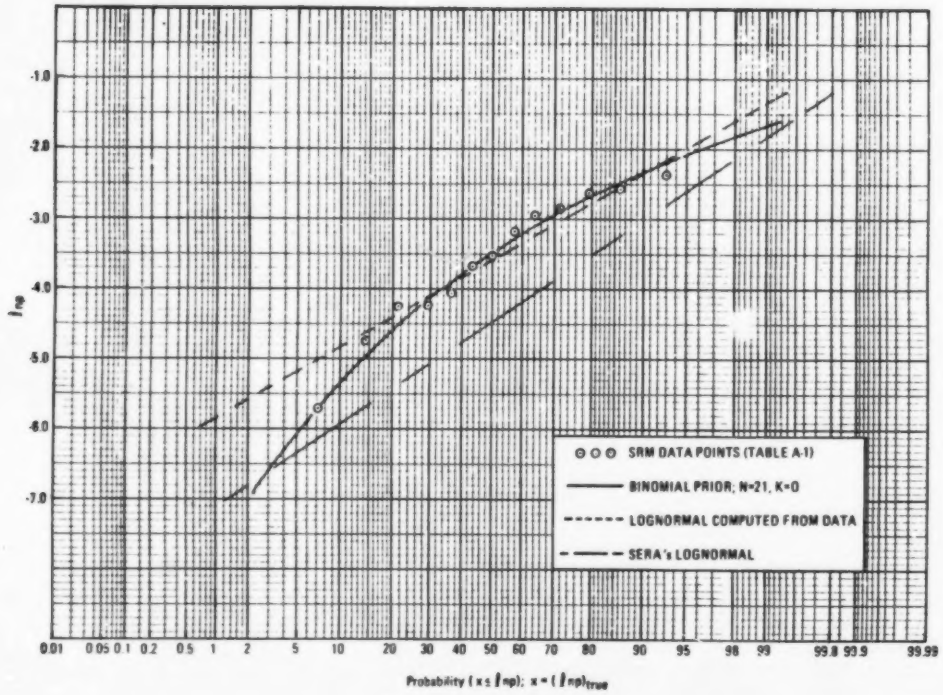

FIGURE 1. COMPARISON OF BAYESIAN PRIORS

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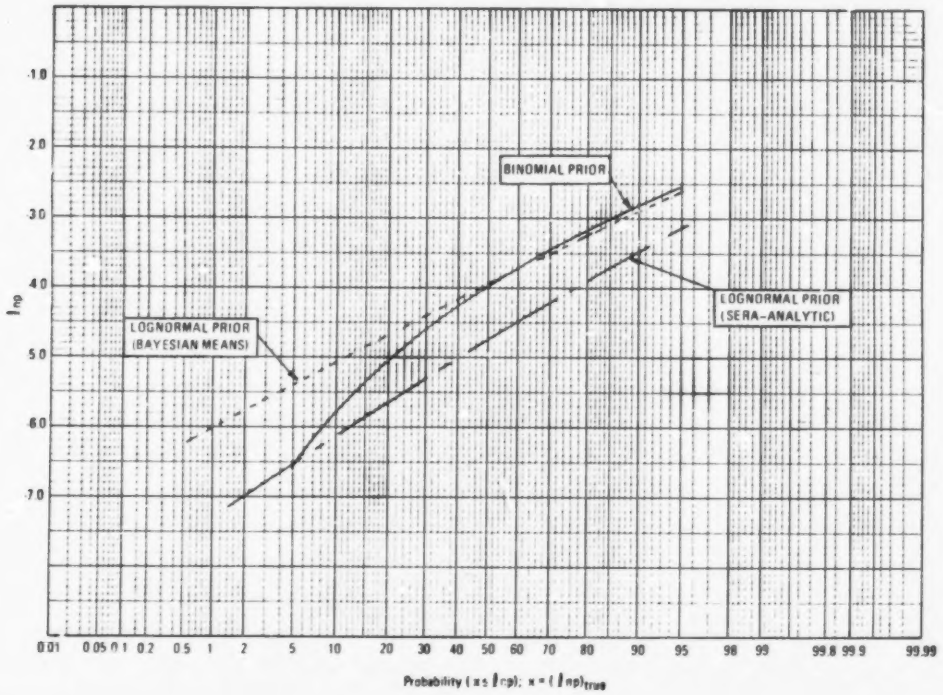

FIGURE 2. SRB POSTERIOR DISTRIBUTIONS

TABLE 1 COMPARISON OF POSTERIOR STATISTICS

	SERA Lognormal		Detailed Models	
	Discrete	Analytic	Lognormal	Binomial
Mean	0.014	0.0141	0.0265	0.0270
Median	0.0099	0.0087*	0.019*	0.0191
0.05 Fractile	0.0031	0.0014*	0.0045*	0.00142
0.95 Fractile	0.0311	0.043*	0.073*	0.0798
Standard deviation	0.0141	0.0156	0.0247	0.0263

*These fractiles were obtained by interpolating the appropriate CDFs in Figure 2.

The effect of item 2 can be evaluated by comparing results from priors based on the complete data set (columns 3 and 4) with column 2. Here, the means and medians are larger by a factor of about 2 using more detailed models for the priors. The binomial prior, which gives the best representation of the SRM data points, shows a range of a factor of about 50 between 0.05 and 0.95 fractiles.

In sum, regarding SRB failure probability, we conclude that there is no evidence of learning that would modify reliability estimates; therefore it is prudent to use these historical data in nuclear risk assessment. The most detailed calculations show a failure probability approaching 0.03 per motor per launch. This should be given due consideration while steps are being taken to identify and remove the design faults specifically responsible for the Challenger accident.

3. NON-SRB FAILURE MODES

Sandia investigated five issues raised by SERA pertaining to estimation of failure rates for VRM's other than VRM-2. The issues raised were:

a. Impact of dependent versus independent sampling.

b. Impact of adding quantiles of individual distributions to form quantiles of summed failure rates.

c. Effect of NASA-supplied criticality factors.

d. Effect of 60% versus 90% interval assumptions.

e. Effect of K-factors.

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We feel that the methodology used by Sandia in this part of the evaluation was apt and systematic and that the results of the impact studies were quite illuminating. First, Monte Carlo simulations were performed to obtain failure rate distributions using Wiggins' assumption and modeling for one VRM (No. 6: External tank punctured) these duplicated Wiggins results within acceptable deviations. Then the effect of changes in modeling recommended by SERA for each issue was examined in turn.

Sandia, in addition evaluated the merits of SERA's recommendations with respect to these issues. In these evaluations, we feel, the Sandia conclusions were not uniformly useful. The results of the impact analysis and Sandia's conclusions are reviewed, summarily, in the following paragraphs.

a. Dependent versus Independent Sampling

SERA recommended and Sandia concurred that dependent sampling for identical composite components - i.e., a specific failure rate selected for a component during each Monte Carlo simulation should be assigned to all identical components - is more justifiable than is independent sampling. Sandia's calculations showed little difference in results when dependent sampling replaced Wiggins' independent sampling in the simulations.

b. Impact of Adding Quantiles

Both SERA and Sandia agree that adding of quantiles of individual distributions for sub-components to obtain quantiles of the summed failure rates is incorrect. The effect of combining these distributions properly by Monte Carlo simulation was evaluated as a factor of 2 reduction in the mean VRM failure rate while the median failure rate was reduced by a factor of about 3. The combination of using dependent sampling at both subcomponent (instead of adding quantiles) and composite component levels produced no additional change in the mean but a slight additional reduction in the median VRM-6 failure rate.

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c. Effect of NASA-supplied Criticality Factors

In this case Sandia included 2 variations in the simulations, compared with the Wiggins model. Dependent sampling at the composite component level (Item a) was retained and the criticality factors were omitted. The net effect was about a factor of 3 increase in the VRM-6 failure rate mean and median values. Therefore, the effect of the criticality factor omission alone in this VRM is somewhat smaller than a factor of 3.

Sandia remarks that use of factors of this type (frequently referred to as beta-factors) to allocate failure rates among failure modes is not uncommon. On the other hand specification of beta-factors is normally done using historical data or a defensible analytic method. That is not the case here and as a matter of fact, these factors were not used in the original Wiggins calculations for VRMs identified during the period between MECO and payload separation (Ref. 2). We conclude, as expressed in the SERA report, that these factors should not be used.

d. Effect of 60% versus 90% interval assumptions

Sandia performed simulations in which the lower and upper bound failure rates for each component were assumed to represent the 20th and 80th percentiles of the distributions, rather than the 5th and 95th percentiles used in the Reactor Safety Study (RSS) and by Wiggins. The simulations also incorporated dependency at the composite component level (item a).

Results of the calculations showed enormous increases in fractiles and mean of the VRM-6 failure rate distribution using the 60% compared to the 90% interval. For example, the mean failure rate was increased by a factor of 500. This extreme sensitivity is consistent with SERA's assessment.

However, Sandia dismissed SERA's assertion that the 60% interval should replace the 90% interval in failure rate modeling.

The reasons for this conclusion were:

(1) Arguments by SERA that subjective estimates tend to underestimate uncertainty didn't apply since the RSS incorporated actual data from several sources.

(2) The IPPSS authors (referenced by SERA) broadened the range of uncertainty relative to the RSS procedure to reflect their state of knowledge of the range of uncertainty for the Indian Point Nuclear Plant. This assumption does not necessarily apply to the uncertainties expected in the Shuttle analyses.

Rather than pursue this qualitative procedure for estimating statistics of failure rate distributions we have chosen to review data presented in the RSS (Ref. 6, Appendix III) to derive quantitative estimates of the probability interval spanned by RSS selection of lower and upper failure rate bounds. The first step was to compile statistics on the number of data sources among the sixty component/ failure mode entries in Table III 2-1 of Ref. 6. More than 90% of the sixty entries had less than 13 data sources. The median number of data sources for these components was four.

For this reason, we examined statistics of the failure rate distributions for the seven component/failure modes in the set having four data sources. The data points in each case were plotted on log normal graph paper using a rank-order procedure (see Appendix C). Upper and lower failure rate bounds estimated in the RSS were then used to evaluate the probability interval spanned. Results of the study are given in Table 2.

We observe, first, that the individual data sets should be used to model distributions of failure rates, rather than estimate statistics of the distributions subjectively. Secondly, if one were to assign a single probability interval for the upper and lower RSS bounds, choice of 60% is better supported by this sample of individual data sets than is 90%.

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TABLE 2 - PROBAILITY INTERVAL FOR INDIVIDUAL COMPONENTS

Case	Component/Failure Mode	Interval Spanned by $\lambda_L, \lambda_{U(\%)}$
1	Check valve/reverse leak	55
2	Check valve/external leak	63
3	Relief valve/failure to open	82
4	Relief valve/premature open	99
5	Clutch mech/failure to open	52
6	Switches/contacts short	48
7	Fuses/failure to open	27

We conclude that there is considerable uncertainty in the RSS failure rate distributions, that the 60% range assumption is justified as a representative value and that, in keeping with both SERA and Sandia estimates, the Wiggins failure rates may be underestimated by a potentially large factor for this single reason.

e. Effect of K-factors

Sandia applied a K-factor of 6 based on the Convair environmental model in its analyses for the Centaur. The results showed, not surprisingly, that the quantiles of the resulting distribution were all increased by a factor of 6.

Sandia concurs with the use of K-factors representing the effect of different operating environments on the frequency of failure for a given part, and we certainly do. Indeed, MIL-HDBK-217D admonishes the reliability analyst to use such factors (designated π_g in their nomenclature); typical values for electronic and passive electrical devices range from 20-60, but those appropriate for mechanical parts may be smaller, as indicated by the General Dynamics study.

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In sum, considering the effects of modifying VRM failure rate estimates in accordance with SERA recommendations, we think that for certain VRM's, the failure rate may be increased by a factor as large as 1000. That this is possible is demonstrated by comparing curve 7 in Sandia's Figure 4-8 (attached), after a small leftward adjustment to correct for addition of quantiles, with curve 1. The various quantiles are displaced by about 3 orders of magnitude and the means are even more disparate. The differences between our assessment and Sandia's owes largely to our different evaluation of uncertainties implicit in the RSS failure rate models.

4. BASIC METHODOLOGICAL ISSUES

SERA criticized Wiggins' selection of Vehicle Response Modes because they were not disjoint, i.e. certain of the VRMs were consequences of other VRMs, that they were not a complete set, and finally that they could not, in all cases, be correlated with one or more discrete sequences of events called accident scenarios.

Sandia agreed with these criticisms but appeared unimpressed by these inadequacies or deficiencies in the Wiggins study. Indeed, Sandia suggests that those deficiencies may be remedied at a later time, during the review process. However, the purpose of the Wiggins study, as modified, was to provide data which could be used to estimate probabilities for important accident scenarios. This is a significant step in the risk analysis process; incompleteness or inapplicability of the work is not a trival shortcoming in our opinion. Adequate VRMs and accident scenarios are still required.

The last item among the basic issues we consider in this review is the exclusion of certain kinds of failures in the Wiggins work. SERA pointed out that omission of common cause failures, maintenance equipment failures, and undetected, pre-existing failures as well as personnel and software errors can cause underestimation of failure rates or probabilities. Their estimate of the error factor of 10 to 100 is indeed unsupported, as pointed out by Sandia.

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SERA AS BEFORE WITH A K-FACTOR OF 6 ADDED

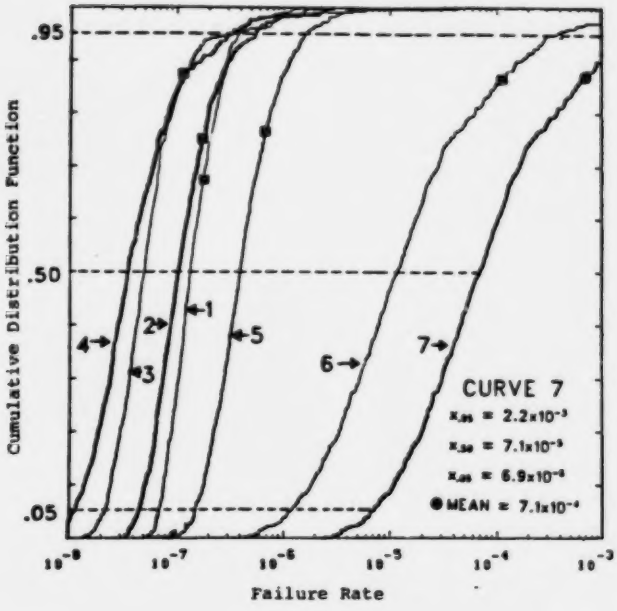

Figure 4-8. The Effect of Using a k-Factor of 6 is Shown by Comparing Curve 7 (with) and Curve 6 (without).

EXCERPTED FROM REFERENCE 5

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Sandia also states, "given the continued predominance of VRM-2 it is possible, however, that the ultimate impact (of the above failures and errors) on the risk from the Shuttle could be small." Thus, Sandia's review excluded consideration of these failures and errors for VRM-2. Evidence available to the public concerning the Challenger accident including:

- possibly non-redundant O-rings sealing the SRB casing joints
- possibly inappropriate SRB assembly procedures
- non-reporting of unusual temperature measurements

and

- a faulty management information system

appears to make SERA's assessment almost prophetic and Sandia's superficial.

A second point relates to Sandia's conclusion that VRM-2 failures predominate in the risk asssessment. We consider this judgment to be premature, since it is not clear at the present time which among the accident scenarios contributes most to the risk from radiative exposure.

5. CONCLUSIONS

Our review addressed three areas in which Sandia concentrated attention in their review of Wiggins' and SERA's reports: SRB burn-through failures, failure rate estimates for all other VRMs, and basic methodological issues. The conclusions drawn from our review follow:

a. SRB burn-through

(1) There is no evidence suggesting that learning effects have reduced the SRB failure probability.

(2) The best estimate of the mean SRB failure probability derived from unweighted historical data is about 0.027 (1/37) per motor per launch, as opposed to the 0.014 given in the SERA report.

b. Failure Rates for other VRMs

(1) Representations of lower and upper bounds of failure rates in the Reactor Safety Study as 5th and 95th percentiles generally underestimates uncertainties in the failure rate distributions.

(2) The Wiggins failure rates may be underestimated by as much as a factor of 1,000 owing to the 90% interval assumption, omission of K-factors and inclusion of the NASA-factors.

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c. Basic Methodological issues

(1) Adequate VHM/accident scenario definition, quantification and correlation are necessary for risk analysis and are still not available.

(2) Consideration of SERA-cited omissions (Ref. 4, p. 76) is vital for realistic reliability estimates.

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6. REFERENCES

1. "Space Shuttle Range Safety Hazards Analysis," James B. Baeker, J.H. Wiggins Co. Technical Report No. 81-1329, July 1981.

2. "Development of STS Failure Probabilities-MECO to Payload Separation," J.H. Wiggins Co. Technical Report No. 79-1359, October 1979.

3. "Development of STS/Centaur Failure Probabilities-Liftoff to Centaur Separation," James M. Hudson, J.H. Wiggins Report No. 82-1404, February 1982.

4. "Review of Shuttle/Centaur Failure Probability Estimates for Space Nuclear Mission Applications," R.K. Weatherwax, E.W. Colglazier, (SERA, Inc) Air Force Weapons Laboratory Report No. AFWL-TR-83-61, December 1983.

5. "Review and Evaluation of Wiggins' and SERA's Space Shuttle Range Safety Hazards Reports for the Air Force Weapons Laboratory," D.D. Carlson, et al Sandia National Laboratories Report No. SAND 84-1579, December 1984.

6. "Reactor Safety Study," Nuclear Regulatory Commission, Accession Number PB-248204, October 1975.

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A-1

APPENDIX A
BAYESIAN ANALYSIS OF SRM AND SHUTTLE EXPERIENCE

Subgroups of SRM data for each type of motor can be used to infer failure statistics for that motor. A procedure for doing this is to perform a Bayesian analysis assuming a uniform prior i.e. $f(p) = 0$, for p on (0,1).

For N trials and K failures of a given motor, the posterior density is

$$h_N(p/K) = C(N,K)\,(N+1)\,p^K(1-p)^{N-K}$$

where $C(N,K) = N!/(N-K)!\,K!$

and the mean failure probability is

$$\langle p \rangle = (K+1)/(N+2).$$

The CDF is $H_N(p/K) = \sum_{m=0}^{N-K} C(N+1, m)\, p^{N+1-m}(1-p)^m$

Means were calculated for each of the 13 motor types tabulated by Wiggins. The number of trials for second stages is the number of launches reduced by the number of first stage failures, whether confirmed or suspected burn-throughs. Only confirmed first and second stage burn-throughs were considered as failures. The results are shown in Table A-1.

The natural logarithms of individual means were ordered from small to large and assigned a fractile value given by m/(M+1) where M is the total number of statistics (13) and m is the sequence index of the individual means. In this case the fractiles are integral multiples of 1/14.

For an unweighted historical analysis, i.e., where the possibility of learning or dislearning is ignored, these fractiles approximate the cumulative distribution for SRM motor failure probability. Estimates for the means and standard deviation of this distribution are -3.59 and 0.975, respectively. The fractiles are plotted as discrete points in Figure 1.

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TABLE A-1. SRM STATISTICS

SRM Type	Stage	Attempts	Failures	p	ln (p)	Sequence Number	Fractile
Polaris A-1	1	164	4	0.030	-3.50	7	0.50
	2	158	8	0.056	-2.88	10	0.71
A-2	1	119	4	0.041	-3.19	8	0.57
	2	113	1	0.017	-4.05	5	0.36
A-3	1	203	2	0.015	-4.22	4	0.29
	2	198	4	0.025	-3.69	6	0.43
Poseidon	1	67	0	0.014	-4.23	3	0.21
	2	63	5	0.092	-2.38	13	0.93
Trident	1	25	1	0.074	-2.60	11	0.79
	2	24	1	0.077	-2.56	12	0.86
Castor II	1	600	1	0.0033	-5.71	1	0.07
Castor IV	1	36	1	0.053	-2.94	9	0.64
Titan	1	110	0	0.0089	-4.72	2	0.14

B-1
APPENDIX B

ANALYTIC CALCULATION OF THE POSTERIOR DISTRIBUTIONS

Two kinds of prior distributions are used: lognormal and binomial. In all cases, the data set is represented by a binomial distribution of 14 attempts and no failures, i.e.

$$h_{14}(p/0) = 15\,(1-p)^{14}$$

1. Lognormal Prior

The CDF is:

$$H(p) = M \sum_{m=0}^{14} C(14,m)\,(-1)^m \exp\left[mx + m^2 S^2/2\right] \cdot Q\left[\left(y - (x + mS^2)\right)/S\right]$$

where $y = \ln p$

$C(14, m) = 14!/(14-m)!\,m!$

x = mean value for $\ln p$

S = standard deviation for $\ln p$

Q = standard normal probability function.

and

$$M = \sum_{m=0}^{14} C(14,m)(-1)^m \exp\left[mx + m^2S^2/2\right] \cdot Q\left[-(x + mS^2)/S\right]$$

The first and second moments are calculated from the expression for H(p) by setting y = 0 and replacing m within the square brackets by (m+1) and (m+2), respectively.

2. Binomial Prior

The binomial prior which fits the set of SRM mean failure probabilities is that for 21 attempts, no failures. The normalized prior density is:

$$h(p) = 22\,(1-p)^{21}$$

When this prior density is combined wtih the Shuttle data set comprising 14

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C-1

APPENDIX C

RANK-ORDER METHOD - A SIMPLE EXAMPLE

RSS Data: Check Valve/Reverse Leakage $\lambda_L = 1 \times 10^{-7}$, $\lambda_U = 1 \times 10^{-6}$

Failure Rate, (Hr)$^{-1}$		ln (λ)	Fractile*
As Presented	Ordered		
2×10^{-7}	1×10^{-7}	-16.1	0.2
1×10^{-6}	2×10^{-7}	-15.4	0.4
1×10^{-7}	6×10^{-7}	-14.3	0.6
6×10^{-7}	1×10^{-6}	-13.8	0.8

*Fractile = m/(M + 1):

m = sequence number of the ordered failure rates.

M = number of data points.

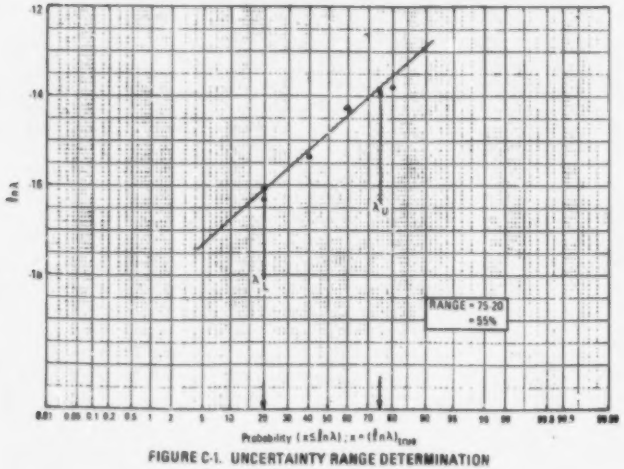

FIGURE C-1. UNCERTAINTY RANGE DETERMINATION

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